The TREND IN ENGINEERING

at the University of Washington

In this issue:

LIGHTWEIGHT AGGREGATE FROM PACIFIC NORTHWEST CLAYS AND SHALES

HARDBOARD PANELS FOR LOW-FREQUENCY SOUND ABSORPTION

HEAVY AGGREGATE CONCRETE

EXPERIMENTAL STRESS ANALYSIS AS AN AID TO MACHINE DESIGN

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EFFECT OF DIELECTRIC HEATING ON CATALYST ACTIVITY

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Acoustical Devices of Ancient Theatres

THE VOICE EXECUTES ITS MOVEMENTS in concentric circles; but while in the case of water the circles move horizontally on a plane surface, the voice not only proceeds horizontally, but also ascends vertically by regular stages. Therefore . . . the first wave, when there is no obstruction to interrupt it, does not break up the second or the following waves, but they all reach the ears of the lowest and highest spectators without an echo.

"Hence the ancient architects, following in the footsteps of nature,* perfected the ascending rows of seats in theatres from their investigations of the ascending voice, and, by means of the canonical theory of the mathematicians and that of the musicians, endeavoured to make every voice uttered on the stage come with greater clearness and sweetness to the ears of the audience. For just as musical instruments are brought to perfection of clearness in the sound of their strings by means of bronze plates . . . so the ancients devised methods of increasing the power of the voice in theatres through the application of harmonics.

"In accordance with . . . mathematical ratios, let bronze vessels be made, proportionate to the size of the theatre, and let them be so fashioned that, when touched, they may produce with one another the notes of the fourth, the fifth, and so on up to the double octave. Then, having constructed niches in between the seats of the theatre, let the vessels be arranged in them, in accordance with musical laws, in such a way that they nowhere touch the wall, but have a clear space all round them and room over their tops. They should be set upside down, and be supported on the side facing the stage by wedges not less than half a foot high. Opposite each niche, apertures should be left in the surface of the seat next below, two feet long and half a foot deep.

"The arrangement of these vessels, with reference to the situations in which they should be placed, may be described as follows. If the theatre be of no great size, mark out a horizontal range halfway up, and in it construct thirteen arched niches with twelve equal spaces between them [for bronze vessels giving the notes in (a) of the illustration]. . . .

"On this principle of arrangement, the voice, uttered from the stage as from a centre, and spreading and striking against the cavities of the different vessels, as it comes in contact with them, will be increased in clearness of sound, and will wake an harmonious note in unison with itself.

"But if the theatre be rather large, let its height be divided into four parts, so that three horizontal ranges of niches may be marked out and constructed: one for the enharmonic, another for the chromatic, and the third for the diatonic system. Beginning with the bottom range, let the arrangement be as described above in the case of a smaller theatre, but on the enharmonic system (a).

"In the middle range, place . . . the vessels which give the notes [of the chromatic system (b)]. . . .

"In the highest division and range of niches, place vessels fashioned so as to give the notes [of the diatonic system (c)]. . . .

"Somebody will perhaps say that many theatres are built every year in Rome, and that in them no attention at all is paid to these principles; but he will be in error, from the fact that all our public theatres made of wood contain a great deal of boarding, which must be resonant. This may be observed from the behaviour of those who sing to the lyre, who, when they wish to sing in a higher key, turn towards the folding doors on the stage, and thus by their aid are reinforced with a sound in harmony with the voice. But when theatres are built of solid materials like masonry, stone, or marble, which cannot be resonant, then the principles of the bronze vessels must be applied. . . .

"Many skillful architects, in constructing theatres in small towns, have, for lack of means, taken large jars made of clay, but similarly resonant, and have produced very advantageous results by arranging them on the principles described."—VITRUVIUS, *Ten Books on Architecture*, Bk. V. Translation of H. M. Morgan, Cambridge-Harvard Univ. Press, 1914.

*"We have, in the determination of the numerical relation between pitch and string length, perhaps the first application of mathematics to the phenomena of nature."—*Source Book in Greek Science*, Cohen and Drabkin, N.Y., McGraw-Hill, 1948.

THE ENGINEERING EXPERIMENT STATION of the University of Washington was established in December, 1917, to coordinate investigations in progress and to facilitate the development of engineering and industrial research in the University. Its purpose is to aid in the industrial development of the state and nation by scientific research and by furnishing information for the solution of engineering problems.

The scope of the work is three-fold:

(1) to investigate and publish information concerning engineering problems of a more or less general nature that would be helpful in municipal, rural, and industrial affairs;

(2) to undertake extended research and to publish reports on engineering and scientific problems;

(3) to provide opportunities for graduate engineers to conduct research under conditions that will most effectively prepare them for professional service.

For administrative purposes the work of the Station is organized into nine divisions:

1. Aeronautical Engineering
2. Chemical Engineering, Industrial Chemistry
3. Civil Engineering
4. Electrical Engineering
5. Forest Products
6. Geology
7. Mechanical Engineering
8. Mining, Metallurgical, Ceramic Engineering
9. Physics Standards and Tests

The control of the Station is vested in a Station Board consisting of the President of the University, the Dean of the College of Engineering as chairman, the Director of the Station, and members of the faculty, representative of the administrative divisions. The Board determines the character of the investigations to be undertaken and supervises the work.

The Station offers a substantial number of research fellowships to highly qualified graduate students who work under the direct supervision of the faculty of the various divisions. Results of major investigations are published in the form of bulletins and reports. Current research findings from the Station's fellowship projects, as well as accounts of its activities, appear in the quarterly journal, *The Trend in Engineering at the University of Washington*. Reprints of articles by members of the engineering faculty and graduate students published in recognized technical journals are also issued by the Station. Requests for copies of the publications and inquiries for information on engineering and industrial problems should be addressed to the Director, Engineering Experiment Station, University of Washington, Seattle 5.

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FRONT PAGE

THE VALUE OF VITRUVIUS, Roman architect and engineer (1st century A.D.), and acknowledged architectural authority during the Renaissance, is today chiefly that of an encyclopedic reporter. Without his *Ten Books on Architecture* much of our information regarding the lore of ancient Greece would be lost. His treatment of acoustics in the theatre is based on the "system" of Aristoxenus (pupil of Aristotle, 4th century, B.C.), who attempted in his *Harmonics* to reconcile the mathematical and sensory approaches to music.

The Greeks had mastered the mathematical antecedents of sound at a very early date, nor was any substantial advance in practical acoustics made from that time up to the present century. Examples of the earthenware vessels, to which Vitruvius refers, have been found. The bronze ones, no doubt, were melted down and used for other purposes.

LEGEND

FIGURE 1

(a) *Upper Left*
Left to right: Samples showing overbloated, properly bloated, and underbloated particles

(b) *Center*
Rotary Kiln

(c) *Lower Right*
Concrete Cylinders Broken in Compression

Lightweight Aggregate from Pacific Northwest Clays and Shales

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The increasing cost of steel and the frequent shortage of supply of this material in recent years have required the construction engineer to turn his attention to the possibilities of lightweight aggregate concrete as a building material. By utilizing a lower density aggregate, the size and weight of structural steel units or reinforcing steel can be reduced substantially. (See Table I.) The Pacific Northwest, although blessed with ample supplies of low fusion clay, generally considered to be a prerequisite for the production of lightweight aggregates, has been far behind the rest of the United States in the production of lightweight concrete, although locally available pumice has been utilized to a considerable extent as an aggregate.

These considerations led to an initial survey of local raw materials during the summer of 1949. This was a joint project, sponsored by the Engineering Experiment Station and the Northwest Experiment Station of the United States Bureau of Mines, and was supervised by Hal J. Kelly, of the latter organization. During the following year, the Experiment Station established Project Number 73, with Dr. Peter D. Johnson, then assistant professor of ceramic engineering, as supervisor. The project received financial support from a group of structural clay products manufacturers and cement and concrete products manufacturers in the state.* The investigation was carried on by junior authors Riley (in 1951) and Shapiro (in 1952), and the supervision was assumed by the senior author upon the resignation of Dr. Johnson in April, 1951.

H. L. Shapiro

J. I. Mueller

The objectives of this research were (1) to continue preliminary testing of various Northwest clays to determine their loss in weight and bloating characteristics in stationary laboratory kilns, (2) to design and construct a small rotary kiln, and (3) to use this kiln for pilot-plant tests of clays deemed from the results of (1) to offer the most promising possibilities.

A lightweight aggregate concrete should have the following physical properties:[1,2]

1. High strength-to-weight ratio: necessary to save weight and strength. ASTM specification C 130-42 requires a maximum of 75 pounds per cubic foot for fine aggregates and 50 pounds per cubic foot for coarse aggregates.
2. Good workability: necessary for the complete filling of forms with a minimum of voids. Rounded aggregate particles give best workability.
3. Low absorption of water by the aggregate: to prevent dehydration of the cement.
4. Uniform size gradation: to improve the packing of the particles and increase the strength.
5. Chemical inertness: to prevent decomposition of the cement by impurities in the aggregate.
6. Low cost: to permit lightweight concrete to compete with standard concretes.

In order to produce bloating of clays or shales, the raw material must be heated until it is in a semi-molten, or pyroplastic condition and its surface is

* Builders Brick Co. (Seattle); Seattle Brick and Tile Co. (Seattle); Washington Brick and Lime Co. (Spokane); Graystone Products Co. (Seattle); Northwest Portland Cement Co. (Seattle); Olympic Portland Cement Co., Ltd. (Bellingham); Superior Portland Cement Co., Inc. (Seattle).

TABLE I

AGGREGATE PROPERTIES*

AGGREGATE	AGGREGATE DENSITY (lb/cu ft)	CONCRETE DENSITY (lb/cu ft)
Gravel	120	150
Sand	90-100	150
Crushed stone	100	145
Crushed bank slag	80	110-130
Haydite†	40-60	100-120
Foamed slag	40-60	90-100
Cinders	40-50 (+sand)	110-115
Pumice	30-60	60-90
Diatomite	28-40	55-70
Perlite	6-16	40-65
Vermiculite	6-10	25-50

*Compiled by the Office of Housing Expediter, Washington, D.C.
†Registered trade name for bloated clays and shales.

impervious and viscous.[1,2,3,4] At this time, some material, generally an impurity, must be decomposing, and the resulting gases will be trapped within the mass. The mass, on cooling rapidly, retains this vesicular structure, and its strength depends upon these pores being uniformly small and surrounded with a tough, yet thin skin. Figure 1(a) shows typical examples of poor and successful bloating.

Raw Materials

The majority of the clays tested were collected and tested under the supervision of Kelly and are described in an unpublished report of the Northwest Experiment Station of the U. S. Bureau of Mines.[5] Samples numbered below 91 were first tested by Kelly, the remaining numbered samples having been collected under the cooperative project but not tested. The Oregon shale referred to below is at present in commercial use and serves as a standard in this investigation. The following list gives the location and brief description of the materials utilized in the project:

Sample 73: A shale from Kummer Mine Number 4, 2,000 feet north of Green River, west of Highway 5.

Sample 77: A dark, plastic shale from the northern slope of Cedar Mountain, King County, 8 miles east of Renton on Highway 5.

Sample 81: A sandy shale from outcrops and road cuts one mile northeast of Waterman Point, Kitsap County, at the northwest point of the peninsula.

Sample 110: A thin-bedded shale, from a roadcut 2,000 feet southwest of Newcastle, 1,000 feet north of Boren Lake, King County.

Sample 118: A black, sandy, weathered shale from a roadcut 500 feet south of the junction of Highway 5 and Lake Young's road, six miles east of Renton, King County, Washington.

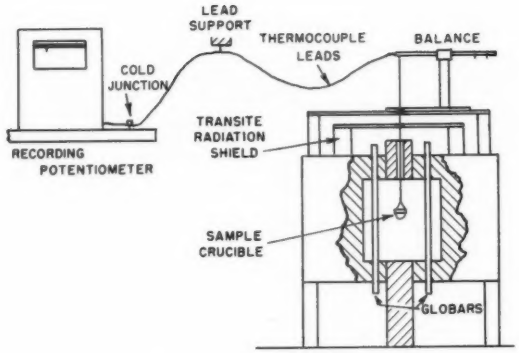

FIG. 2. WEIGHT-LOSS KILN

Sample 119: A black, sandy, weathered shale from a roadcut 500 feet south of Sample 118.

Renton Shale:* A composite of Samples 50, 51, and 120.[5] These are gray, sandy shales interbedded with sandstone, about six miles east of Renton, along Highway 5.

Oregon Shale: A massive siltstone composed largely of products of volcanic extrusion with carbonaceous materials and fossils. This material is used by Northwest Aggregate, in Portland, Oregon, for the manufacture of lightweight aggregate in a rotary kiln.[6]

Gladding-McBean Shale: A sandy shale located at the Renton plant of Gladding, McBean & Company.

Centralia Shale: A plastic shale from Centralia, Washington.

Superior Clay: A Puget Sound glacial clay from the West Marginal Way pit of the Superior Portland Cement Company, Seattle, Washington.

Bellingham Shale: A coal shale from Bellingham, Washington. The sample was collected by C. W. Harkness.

Weight-Loss Test

A weight-loss test was used to determine the temperatures at which the gases were evolved from a clay. It was believed, if the gases in a nonbloater were found to be given off at a temperature near the point where the clay had reached a pyroplastic condition, that it might be possible to produce bloating by adjusting the softening point of the clay to coincide with the temperature at maximum gas evolution.

Each clay sample was ground to pass 100 mesh, placed in a crucible, and suspended from the arm of a balance in a small kiln (Fig. 2) equipped with

* Samples 50, 51, and 119 appear to be from the same general deposit. Samples 7, 118, 119, and Renton Shale were taken from deposits within one mile of each other.

TABLE II

WEIGHT LOSS VERSUS BLOATING

SAMPLE	TOTAL WT LOSS AT 1150° C (%)	PRELIMINARY BLOATING TEST	
		QUALITY OF BLOATING	BLOATING TEMP (Deg C)
Oregon Shale...	....	Excellent	1120
Sample 77.....	8.9	Good	1210
Belling. Shale...	8.5	Good	1110
Sample 81.....	10.4	Good	1096
Sample 73.....	19.7	Good	1300
Sample 110.....	7.6	Fair	1240
Sample 118.....	7.5	Poor	1310
Sample 119.....	6.9	None	....
Superior Clay...	4.7	None	1130

Globar resistance elements. A set of chromel-alumel thermocouple leads hung from the balance arm, and were imbedded in the sample. The furnace was heated at a rate of 10° C per minute, and the temperature within the sample was recorded on a strip-chart potentiometer. By noting the temperature registered when a weighing was made, a plot of loss in weight versus temperature was made.

These curves showed that the majority of the weight loss took place below 700° C. For most raw materials the beginning of fusion occurs at or above 1100°; therefore, very little gas is given off at the bloating temperature unless the clay is heated fast enough to prevent escape of all the gases before a glassy phase develops. Samples 73, 77, and 81 showed the highest weight loss of the materials tested, and therefore should be good bloaters.

Preliminary Bloating Test

To determine the speed of firing for a bloated aggregate, each sample was ground to pass 65 mesh, mixed with water, and formed into a ball 1.4 cm in diameter. A chromel-alumel thermocouple was embedded in the ball, which was then dried and suspended in the kiln. The furnace and method used was the same as for the weight-loss tests, except that the balance was removed. The initial kiln temperature of 480° C was raised to reach the bloating temperature in from 25 to 40 minutes, approximating commercial firing rates. When bloating was observed, the ball was removed from the kiln. Those samples which were fired above 1150° C were suspended on a chromel wire in the kiln, and a platinum-platinum rhodium thermocouple was used to measure the temperature.

Sample 73 was classified as a high-temperature bloater requiring a firing rate of 40° per minute. Sample 77 had a bloating temperature of 1210° requiring a firing rate of 60° per minute. Sample 81, a low-temperature bloater, could be bloated at 1096° at a rate of 30° per minute. Sample 110 did not appear to be of commercial quality, requiring a high bloating temperature of 1240° and a 60° per minute firing rate. Sample 118 was bloated at 1310°, but exhibited extreme melting which might cause sticking in a rotary kiln. Sample 119 did not contain sufficient gas-producing materials to produce bloating. The Bellingham sample bloated satisfactorily at 1175° with a firing rate of 30° per minute. The Superior clay produced little bloating and was believed to require additives to produce bloating commercially.

TABLE III

OPTIMUM BLOATING TEMPERATURE

SAMPLE	ROTARY KILN TEST		STATIONARY KILN TEST			
	TEMP (Deg C)	TIME (Min)	TEMP (Deg C)	TIME (Min)	TEMP (Deg C)	TIME (Min)
Oregon Shale.....	1100-1160	15	1100	15	1100	30
Renton Shale.....	1175	15	1200	15	1175	30
Centralia Shale.....	1150-1165	15-20	1150	15	1100	30
Glad-McB. Shale.....	1150	20	1175	15	1150	30
Superior Clay.....	1125	10	1125	15	1100	30
Samp. 77.	....	..	1125	15	1110	30
Samp. 110.	....	..	1150	15	1125	30
Samp. 118.	....	..	1165	15	1110	30
Samp. 119.	....	..	1165	15	1150	30

In Table II the correlation between the weight loss and the preliminary bloating test is shown. The quality of bloating was proportional to the total weight loss when fired to 1150° C. The bloating temperature of the sample was that which produced the best aggregate.

Stationary Kiln Bloating Test

Hand-molded one-inch cubes of the raw materials were used for this test. An electric resistance furnace was heated to the desired temperature and the samples were fired at various temperatures for 15 to 30 minutes to determine at what point the lowest density and best structure were obtained. These times represent approximately the upper and lower limits for which a material would remain in the 20-ft rotary kiln, and they also permitted an observation of the variation of optimum bloating temperature with a change in firing time.

Table III shows a comparison of the optimum bloating temperatures in the rotary kiln and in the stationary kiln bloating test.

TABLE IV

Results of Rotary Kiln Test

Sample	Max. Kiln Temp (Deg C)	Time in Kiln (Min)	Aggregate Crushed to Pass 3/8-In.		Uncrushed Aggregate		Concrete (Cement 1: Aggregate 5.8: Water 6.2 gal)			
			Rodded Bulk Density (lb/ft³)	Absorption (%)	Rodded Bulk Density (lb/ft³)	Absorption (%)	Compressive Strength (psi)	Bulk Density (lb/ft³)	Absorption (%)	Workability
Oregon Shale										
B-1	1100	15	46	30	37	20	1890	74	29	Good
B-2	1160	15	46	40	41	17	1780	71	36	Good
Renton Shale										
A-1	1175	15	65	13	55	11	1430	93	20	Fair
A-2	1200	15	50	11	..	..	820	80	18	Fair
A-4	1170	20	81	11	68	8	1200	96	21	Fair
A-5	1170	10	84	13	74	12	....	..	..	....
Centralia Shale										
C-1	1160	15	60	13	59	9	600	74	34	Fair
C-2H	1165	20	58	13	51	9	500	72	34	Fair
C-2L	1150	20	67	12	56	11	700	79	31	Fair
C-3	1150	20	56	17	50	11	....	..	..	....
Glad-McB. Shale										
D-1	1150	20	68	7	62	10	....	..	..	....
D-2	1150	15	72	11	75	10	....	..	..	....
D-3	1170	15	72	11	64	13	....	..	..	....

Oregon Shale, Centralia Shale, and Sample 77 showed a large amount of bloating and wide range of temperatures at which satisfactory bloating occurred.

Renton Shale, Gladding-McBean Shale, Superior Clay, Sample 110, and Sample 119 showed a lower moderate amount of bloating with a tendency to become sticky before a large amount of bloating took place.

The bloating temperatures of samples fired in the rotary kiln compared closely with the bloating temperatures found in the stationary kiln test. Also, the stationary kiln test showed the range of temperature which results in satisfactory bloating of a sample. Indications of the amount of bloating and the point at which a sample would become sticky were shown by the stationary kiln test.

The Rotary Kiln

The rotary kiln, shown in Fig. 1(b), is 20 ft long, and 3 ft in outside diameter, with a 4½-in. firebrick lining. The exhaust end of the kiln is enclosed in a hood to conduct the gases to two axial flow exhaust fans. From the fans the spent gases travel to two 14-in. metal stacks.

On top of the exhaust hood is a storage hopper, with an auger in the bottom to feed the raw material to the kiln. A ¾-in. lump is the maximum size which the auger can handle, and the rate of feed is 15 lb per minute.

The burner end of the kiln is enclosed in a hood to direct the material falling from the kiln into a container. An opening in this hood permits the burner flame to enter the kiln. P. S. 200 fuel oil atomized by compressed air is used, and direct-reading flowmeters measure the rate of flow of oil and air used in combustion.

The Rotary Kiln Test

During these tests the only variables for operation of the kiln were temperature and kiln slope. The kiln slope determined the length of time it took the material to pass through the kiln, or the rate at which it was heated. The feed end of the kiln was at 600° C, and the rotation speed was 70 ft per minute.

The kiln was brought up to the desired temperature and allowed to soak 15 to 30 minutes. Enough minus ¾-in. material was passed through the kiln to yield 100 lb of aggregate, whenever possible. An optical pyrometer determined the maximum kiln temperature. Some of the samples were collected from two firings made at the same temperature.

The aggregate was crushed to pass a ⅜-in. sieve, and absorption was measured by the procedure specified in ASTM C 128-42.

The following concrete mix was used to pour concrete cylinders by the procedure outlined in ASTM C 192-49: cement, 1 cu ft; aggregate, 5.8 cu ft; water, 6.2 gallons. The cylinders were tested for

compressive strength by the procedure outlined in ASTM C 39-49.

Representative samples from the broken cylinders were soaked 24 hours in water, and their weights were obtained when saturated and when saturated and suspended in water. The dry weight of the samples was then obtained and the absorption and bulk density calculated as follows:

$$\% \text{ Absorption} = \frac{(\text{saturated wt}) - (\text{dry wt})}{(\text{dry wt})} \times 100\%$$

$$\text{Bulk Density} = \frac{(\text{dry wt})}{(\text{saturated wt}) - (\text{saturated and suspended wt})} \times 62.4$$

The results of these tests are shown in Table IV. Figure 1(c) shows examples of cylinders broken in compression. The Oregon Shale, used as a standard, produced an aggregate of low bulk density and high absorption at a low firing temperature. The firing rate was 40° per minute and the aggregate produced was of uniform structure. The workability of the concrete mix was good, and the compressive strength approached 2,000 psi.

The Renton Shale produced aggregates of low absorption and fairly high bulk density. The material had a tendency to stick together in the kiln at the higher bloating temperature. The concrete had fair workability and showed highest strength when the material was slightly underbloated. The fracture around the aggregate grains in the concrete cylinders shows that the maximum compressive strength was not reached.

Centralia Shale produced aggregates of low bulk density and low absorption. Of the materials tested in the rotary kiln, this shale produced aggregate which most closely approached the low bulk density of the Oregon Shale. The concrete showed fair workability, the fractures in the concrete cylinder being around the aggregate grains, again indicating that the maximum strength was not reached.

Gladding-McBean Shale produced aggregate of high bulk density and low absorption. This raw material is not highly compacted and the preliminary crushing operation produces a high percentage of fines which cause sticking in the kiln. Elimination of most of the fines in the kiln feed should allow a higher firing temperature, resulting in lower aggregate bulk density.

Conclusions

1. The laboratory testing of clays indicated that some correlation could be obtained as to the expected bloating characteristics of a material in a production operation. This conclusion is of obvious importance when one compares the large number of clays that might be considered bloaters to the few that proved satisfactory, and considers the amount of time and labor saved in being able to utilize small amounts of a material in a short-time test.

2. The 20-ft rotary kiln was able to produce a lightweight aggregate which compared favorably with commercial aggregates. Of all the samples tested, the Centralia Shale was found the most promising for commercial use. The Renton Shale and the Gladding-McBean Shale produced aggregates below the maximum bulk density as specified by the ASTM and are worthy of consideration for production.

3. From the laboratory tests, Samples 77, 81, 118, and the Bellingham Shale appeared to be of sufficient value to justify further testing.

The results of all these tests indicate that clays are available within the state that would be satisfactory for the production of a lightweight aggregate on a commercial scale.

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TRAFFIC ENGINEERS TO MEET IN MAY

The Sixth Northwest Conference on Traffic Engineering will be held in More Hall, University of Washington, on May 21-22, 1953. Topics slated for formal presentation or panel discussion include: highway needs, toll roads and freeways, design and control of limited access highways, parking, minor intersection traffic control. Several nationally prominent speakers are expected to participate, and traffic engineers from all sections of the Pacific Coast will exchange views and experiences on regional problems. Registration will take place in More Hall from 8:30 to 10:00 a.m., Thursday, May 21. The technical sessions will be followed by a field trip on Friday afternoon. Requests for programs should be directed to the general chairman, Professor R. G. Hennes, 121 More Hall.

HARDBOARD PANELS FOR SOUND ABSORPTION AT LOW FREQUENCIES

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One of the major problems in acoustical design of studios and auditoriums is that of obtaining uniform absorption of sound energy throughout the audible frequency range. The absorption coefficients of most commercially produced acoustical materials are much greater at the higher than the lower frequencies. A room acoustically treated with only such a type of material retains an excessive reverberation time at low frequencies. Recognition of the very desirable acoustic properties of some old auditoriums and theaters with wood panel interiors has led to the effort to duplicate these properties in modern studios by the installation of plywood panels of various designs. Although much of this work was done on a purely empirical basis, without determining the absorption coefficients of such panels, some installations gave very satisfactory results.[1,2]

The most efficient use of resonant panels seems to be in combination with existing commercial products, such as acoustic tiles. Inasmuch as the panels are most effective absorbers at low frequencies and the tiles are most effective at high frequencies, the two types of materials supplement each other throughout the audible range. Here again it is important that the designer have available the absorption coefficients of the materials he expects to use.

Project No. 30 of the Engineering Experiment Station was set up in 1949 to investigate absorption coefficients of panels of various materials and shapes. The results of tests by Kenworthy and Burnam[3] with ¼-in. plywood panels showed that such panels, when arranged along a wall with a few inches of air space between the panel and wall, are quite effective as resonant absorbers at the lower frequencies. Tests with panels of irregular shapes (splayed or curved) produced improved acoustical qualities through diffusion of the incident waves. Results showed that absorption of all panels is increased when combined with absorbing materials such as kapok felt. The highest average coefficient for frequencies of 128 cps to 4096 cps was obtained with the absorber on the wall and the panel of splayed (V-shape) design. (See Table I.) The slightly lower values of absorption for the cylindrical panel at low frequencies is probably due to its greater rigidity. However, its recognized value as a diffuse reflector of sound waves offsets its lower absorption when used in certain types of installations.[2]

E. C. Ash, Jr.

In 1951 the project was extended to tests with hardboard panels of several thicknesses, shapes, and backing conditions, which will be described in the following pages. Although some similarity between the acoustic properties of plywood and hardboard was expected, the more uniform and denser structure of hardboard would also lead one to expect some differences. Data again were obtained for octave intervals between frequencies of 128 and 4096 cps.

Apparatus and Procedure

As in the case of the tests on plywood, the work was carried out in the acoustics laboratory of the department of physics. The measurements were made by the recognized reverberation method in a chamber isolated from the rest of the building. The volume of the chamber is considerably smaller than the one of the Acoustical Materials Association Laboratory, and yields coefficients which in general are smaller than those published by the A. M. A. However, it is believed that the values of the coefficients reported here are consistent with values determined under field conditions of panel installation.

A warble-tone oscillator was used as a source of sound. Speaker and microphone positions in the room were such that a uniform or diffuse distribution of sound energy was obtained throughout the room. The oscillator output was amplified to produce an

TABLE I[3]

ABSORPTION COEFFICIENTS FOR VARIOUS ¼-IN. PLYWOOD PANEL CONFIGURATIONS

FREQUENCY (cps)	128	256	512	1024	2048	4096
FLAT PANEL						
No backing	0.16	0.15	0.09	0.07	0.06	0.08
Absorber on wall	0.18	0.17	0.11	0.07	0.07	0.10
Absorber on panel	0.20	0.21	0.12	0.07	0.07	0.10
SPLAYED PANEL						
No backing	0.16	0.10	0.09	0.07	0.08	0.15
Absorber on wall	0.27	0.17	0.14	0.11	0.11	0.18
Absorber on panel	0.21	0.15	0.15	0.11	0.11	0.18
CYLINDRICAL PANEL						
No backing	0.11	0.15	0.13	0.09	0.10	0.10
Absorber on wall	0.16	0.18	0.19	0.13	0.12	0.15
Absorber on panel	0.16	0.22	0.18	0.13	0.12	0.15

intensity in the reverberation room of approximately 100 db. The amplified signal from the microphone was fed into the sound-level recorder, which contained a logarithmic potentiometer, to record the change of sound intensity in decibels.

In all cases the surface area of the test panels was maintained constant at 64 sq ft (i.e., 2 panels 4 by 8 ft). The factors which were varied were panel thickness, shape of the exposed surface, and treatment of the unexposed (back) surface of the panels.

The general construction of the flat, splayed, and curved panels used in this work is shown in cross section in Fig. 1 (a), (b), and (c). All panels were mounted securely by screws on 10-in. centers to a framework of 1-in. by 2-in. Douglas fir strips. The panels were laid on the floor with the back or open side down. In each case a close fit to the floor was obtained, but no special measures were taken to secure the panels to the floor. Inasmuch as the surface area of the hardboard was maintained at 64 sq ft for each pair of panels, the floor area covered by the panels varied.

In making each test, two similar panels were arranged side by side in the center of the floor space. The speaker was placed in its position, the same for every test, and the microphone was arranged in the desired position for the particular run. After the room was closed, a warbled signal was transmitted to the speaker for several seconds until a uniform intensity was indicated on the recorder. Then the signal was cut off, and the decay curve was recorded in intensity versus time. Upon combining data for three microphone positions, a minimum of 135 individual decay curves were recorded at each frequency for each individual panel arrangement.

Hardboard of ⅛-in., $\frac{3}{16}$-in., and ¼-in. thickness was used in making panels of each shape, and each of these 9 pairs of panels was then tested under the

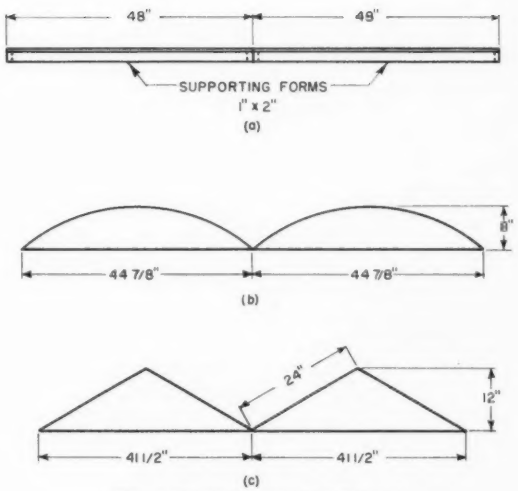


FIG. 1. CROSS SECTION OF PANELS (a) FLAT ,(b) SPLAYED, (c) CURVED

following three conditions of mounting:

1. A given pair of panels was placed on the bare concrete floor.
2. Quilted kapok ½-in. thick was placed on the floor beneath the panel.
3. The quilted kapok was spot-cemented to the back of the hardboard.

In each case an air space was present between the hardboard and the floor, and for each individual arrangement tests were made at frequencies of 128, 256, 512, 1024, 2048, and 4096 cps. For computational purposes it was also necessary to make several determinations of the reverberation time of the empty room.

The original data consisted of the curves produced by the sound-level recorder. The slope of a straight line drawn through the decay portion of the curve could be measured in decibels per second. As the recorder was operated at a paper speed of one centimeter per second, a longitudinal distance measured in centimeters was equal to time in seconds, and as the combination of warble-tone oscillator and sound-level recorder was pre-calibrated for intensity in decibels, it was a simple matter to measure the required time for a drop in intensity of 60 db and to calculate the values of absorption coefficients.

Results

Since results for the nine sets of tests showed only three cases where the ⅛-in. hardboard was not superior to the heavier panels, and even in those exceptions the difference was very slight, the present report will be confined to results of the ⅛-in. panels of the three shapes, each under the three conditions of "no backing," "backing on floor," and "backing spot-cemented to panel."

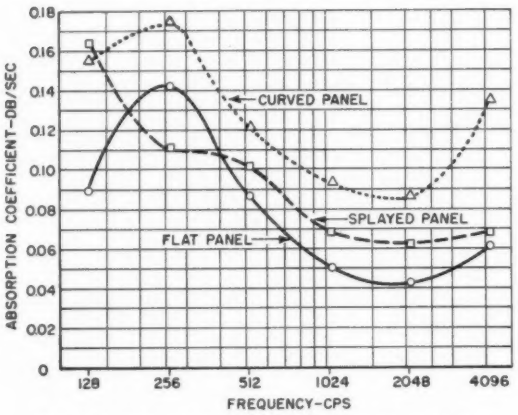


FIG. 2. SOUND ABSORPTION COEFFICIENTS OF 1/8-IN. HARDBOARD PANELS WITHOUT BACKING

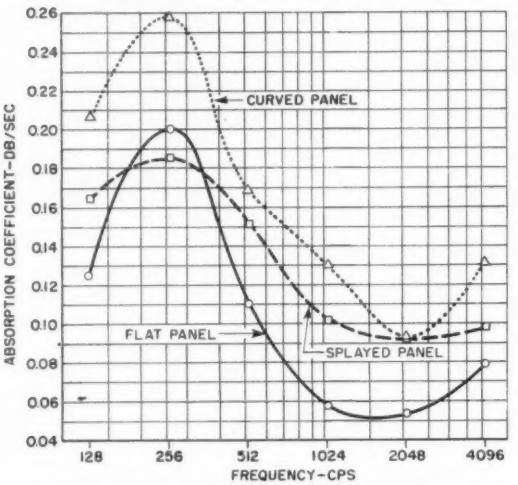


FIG. 3. SOUND ABSORPTION COEFFICIENTS OF 1/8-IN. HARDBOARD PANELS WITH QUILTING SPOT-CEMENTED TO BACK OF PANEL

A quick glance at Table II and the curves of Figs. 2, 3, and 4 showing comparative absorption coefficients for the different backing conditions of the flat, splayed, and curved panels, respectively, reveals the superiority of the curved panels over the other two shapes. For those curved panels mounted with absorbent backing it was necessary to change the absorption coefficient scale in order to keep the curves on the page.

The particular type of backing application had little effect on the splayed panels; but in the case of the flat and curved panels the spot-cemented backing gave slightly better results than did merely placing the quilting on the floor beneath the panels.

In general, the curved panels gave higher coefficients of absorption than did the other shapes. Of

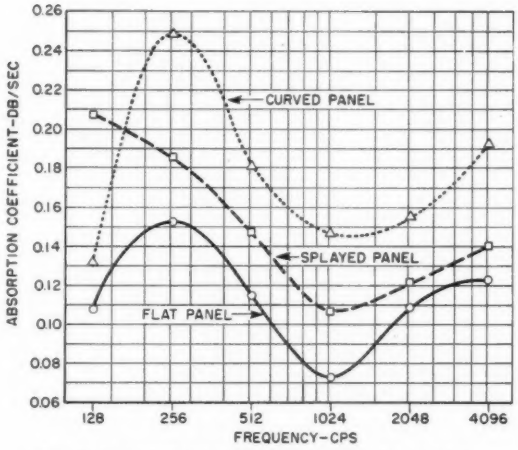


FIG. 4. SOUND ABSORPTION COEFFICIENTS OF 1/8-IN. HARDBOARD PANELS WITH QUILTING ON FLOOR BENEATH PANELS

TABLE II

ABSORPTION COEFFICIENTS FOR VARIOUS 1/8-IN. HARDBOARD PANEL CONFIGURATIONS

FREQUENCY (cps)	128	256	512	1024	2048	4096
FLAT PANEL						
No backing	.09	.14	.09	.05	.04	.06
Absorber spot-cemented to panel	.13	.20	.11	.06	.05	.08
Absorber laid on floor	.11	.15	.12	.07	.11	.12
SPLAYED PANEL						
No backing	.16	.11	.10	.07	.06	.07
Absorber spot-cemented to panel	.16	.19	.15	.10	.09	.10
Absorber laid on floor	.21	.19	.15	.11	.12	.14
CURVED PANEL						
No backing	.16	.18	.12	.09	.09	.14
Absorber spot-cemented to panel	.21	.26	.17	.13	.09	.13
Absorber laid on floor	.13	.25	.18	.15	.16	.19

the curved panels tested, the ones with the backing spot-cemented were superior to the others, though the absorption coefficients for these panels decreased as the thickness of the panels increased.

Conclusions

Hardboard 1/8-in. thick is preferable to the 3/16-in. and 1/4-in. on both economic and performance grounds. In the curved panels of the two thicker types, the 3/16-in. material has considerably better characteristics than the 1/4-in. Proof is not conclusive that still heavier materials may not show some advantages, but there is little evidence here to cause one to expect such results.

(Continued on page 23)

Air-Pollution Problems Excite Wide Interest

ROSS N. KUSIAN

Director, Environmental Research Laboratory

FOLLOWING THE RELEASE, a year ago, of "Report on an Air Pollution Study for the City of Seattle," numerous inquiries were received by the Environmental Research Laboratory which had conducted the survey. With the continued display of interest, a review of recent activities in the atmospheric pollution field seems to be in order.

At the time the report was submitted the plan was to continue one or two basic measurements of the extent of air pollution in Seattle and obtain data by which to predict the effectiveness of any method of control introduced in the future. With the resignation of City Engineer Ralph W. Finke, and change in the city administration under whose authority the study had been conducted, this plan was dropped.

In addition to local groups such as the local League of Women Voters which has included air pollution as one of the subjects in their study course, national attention has been drawn to the results of the Seattle study. Excerpts from the report published in *The Trend* (July, 1952), were reprinted in *Air Repair* (November, 1952), the official publication of the Air Pollution Control Association. Professor Richard W. Tyler, author of the report, was requested to outline the results of the study at the meeting of the Sewage Works Association in Portland, Oregon, October 23, 1952. Professor P. E. Church discussed the meteorological aspects of the work in a paper presented at the National Air Pollution Symposium in Pasadena, California, May 5-6, 1952.

Other communities are also reviewing their air-pollution problems. An excellent example of community action is the work being done by Mr. Leroy Fulton, chairman of the Pollution Committee of the Longview-Kelso Greater Community Council. Mr. Fulton and his committee have engaged in an extensive study of water pollution and are now conducting a similar study of air pollution in their area.

The effect of fluorides on vegetation and on animals feeding on this vegetation has been an extremely important question to agriculturists in the state, with the expansion of industries in which this class of pollutants occurs. An extensive study is currently being done by the Washington State Institute of Technology. Reports of this work are not yet available. Generally, this research agency has specialized in problems concerning specific chemicals, and not in a community over-all problem.

The question of whether air pollution in the state of Washington is sufficiently bad to affect adversely the health of the community has never been settled. Consequently the Washington State Health Council sponsored an investigative committee, composed of a voluntary group of representatives from industry and research agencies, to survey the entire situation. Lacking funds, however, it found itself limited to discussion.

The extent of such health hazards is also being investigated by a special committee of the King County Medical Society, with Dr. Jean Michel as chairman. Their findings have not yet been released.

As a result of these various group activities, House Bill 96 was introduced in the recent legislature calling for creation of an "Office of Air Pollution" within the State Pollution Control Commission. The bill passed the House without the appropriation, but was not passed by the Senate before adjournment. Elimination of the appropriation nullified any value the bill may have had. Also, criticism was expressed that this legislation would duplicate the existing facilities and services of the Environmental Research Laboratory, a research agency sponsored by the University but not financed with state funds.

Today, while many groups continue to discuss the problems involved, city officials are faced with irate citizens blaming industrial plants, and industrial leaders are repeatedly defending their operations. Each group needs impartial technical information and assistance. The Environmental Research Laboratory is prepared to give the following services and facilities:

1. Reports of air-pollution activities from all over the world, collected and indexed, are available to study groups.
2. Lecture-demonstrations with slides and films presenting an impartial review of the problems involved may be requested.
3. In addition to the extensive facilities of the University's College of Engineering and the School of Medicine, the Environmental Research Laboratory has acquired some specialized equipment of its own. For example, portable stack-sampling equipment is available for determining the actual emission of pollutants in any process. A directional dirt-fall collector not only collects air-borne dirt but also records the direction from which it came.

The staff of the Environmental Research Laboratory are ably prepared to offer a unique well-balanced, cooperative, medical-engineering service to any community with air-pollution problems.

HEAVY-AGGREGATE CONCRETE

H. P. MITTET
Assistant Professor of Civil Engineering

H. P. Mittet

Although high-density concretes have been used for counterweights and similar structures requiring large weight and relatively small volume, little consideration had been given to the structural properties of these concretes until they were required for radioactive shielding. The purpose of the present investigation was to determine the characteristics of high-density concretes for use in construction work at Hanford. The project is sponsored by the General Electric Company, which has furnished the aggregates used in the investigation as well as steel punchings, limonite, magnetite, and Hanford sand and gravel.

Magnetite is an iron ore, steel gray to black in color, occurring in large deposits in Canada, the northern and eastern United States, and in Washington and California. Limonite is a hydrated iron oxide, moderately hard, porous and absorptive. It produces a tile-red concrete. This material is also abundant in the United States.

The coarse aggregates used were of one-inch maximum size. The fine aggregates were of average grading except for the limonite, of which 86.5 per cent was coarse, and 13.5 per cent, in the form of stone dust, passed the number 200 sieve. Type II, low alkali Portland cement was used. The slump was 3 inches.

The five concrete mixes used in the investigation (Table I) were tested for volume change, flexural strength, compressive strength, modulus of elasticity, and bond.

Volume Change

The volume change of the concrete was measured by casting a 3- by 3- by 11-in. prismatic specimen. At the center of each end a stainless steel contact plug was imbedded to provide a 10-in. gage length. The form was removed at 24 hours, and the specimen was then stored in a moist closet at 72° F. Length changes were measured with a dial micrometer.

The effect of continuously maintaining within concrete an excess of moisture is to produce an expansion over an extended period of time, due to the continued hydration of the cement. In small members an expansion of 0.0001 in. is seldom attained in less

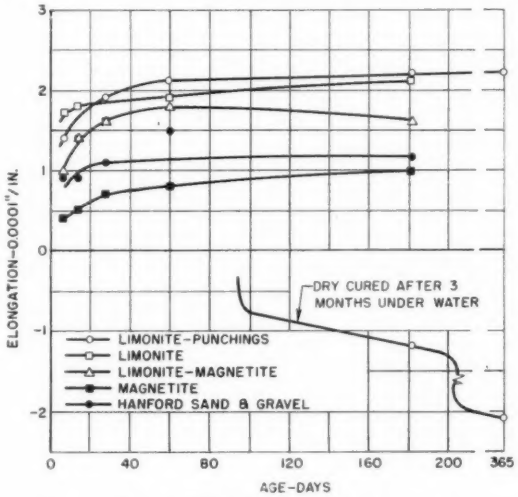


FIG. 1. DIMENSIONAL STABILITY
(Note: An error was apparently made in the 2-month Hanford reading.)

TABLE I

CONCRETE MIXES

MIX NO.	1	2	3	4	5
FINE AGGREGATE	Limonite	Limonite	Limonite	Magnetite	Hanford Sand
COARSE AGGREGATE	Punchings	Limonite	Magnetite	Magnetite	Hanford Gravel
WATER/CEMENT	0.395	0.485	0.467	0.402	0.366
MIX BY WEIGHT	1: 2.01: 4.35	1: 1.97: 2.42	1: 2.18: 2.66	1: 2.42: 2.96	1: 1.59: 1.94
WEIGHT/CU FT	268	185	198	212	154
CEMENT: SACKS/CU YD	10	9	9	9	9

than 3 months. In the present case, the volume change as measured by the change in length of the bars (Fig. 1), indicated a large expansion of the concretes with the exception of the magnetite concrete. This is to be expected because of the high cement content.

Only one group of the volume-change mixes was removed from moisture and permitted to dry out. After three months in moist curing, this group of three of the limonite-punchings concrete specimens were removed from the moist closet and cured in laboratory air for nine months. These specimens, at the end of three months of moist curing, had an expansion over their original length of 0.00021 in. per inch. At the end of the following nine months in dry air, their shrinkage from their original length was in the same proportion: 0.00021 in. per inch. The shrinkage of concrete is more nearly proportional to the quantity of mixing water than to any other single factor. The other mixes containing limonite, on which tests are not yet complete, are expected to have a shrinkage in excess of the limonite-punchings concrete because of their greater water content.

Compressive Strength

The compressive strength of concrete was determined by testing concrete cylinders 6 in. in diameter and 12 in. long. For a given aggregate the strength of concrete is inversely proportional to the water-cement ratio. Comparing the water-cement ratio values for the several mixes and the compressive strength as shown on Fig. 2, the compressive strength of limonite-punchings concrete is found to be much less than might be expected. The punchings used in this concrete were not clean and did not all provide a good bond to the concrete. Some loss of strength can be attributed to this factor.

The value of the modulus of elasticity for each concrete mix was also determined. Figure 3 illustrates the relative elastic properties of these concretes. The curves, when compared with those of Fig. 2, show that the stiffness of the concrete is not proportional to the strength. The limonite-punchings concrete, which had the least compressive strength, had a very high modulus of elasticity. None of the concretes exhibited a straight line stress-strain relationship. In order to apply a straight line relationship the secant modulus was used, taking the slope of the line drawn from the origin to the elongation at a stress of 3,000 psi. Subsequent tests on limonite-punchings concrete cylinders at 6 months and 12 months showed a linear stress-strain relationship.

Flexural Strength

The flexural strength was determined by testing a 6- by 6- by 24-in. beam. This beam spanned 18 in. and was loaded at the one-third points to produce a constant bending moment over the center third. The modulus of rupture was calculated from the bending moment at fracture. Concrete usually has about 10 per cent of the strength in tension that it does in compression. With allowance for stress distribution at variance with the assumed straight line of the modulus of rupture, a close agreement was found with this percentage. Results for the modulus of rupture for the concretes of various ages are shown in Fig. 4. A comparison of Fig. 4 with Fig. 2 reveals a correlation between the two curves. Concretes with

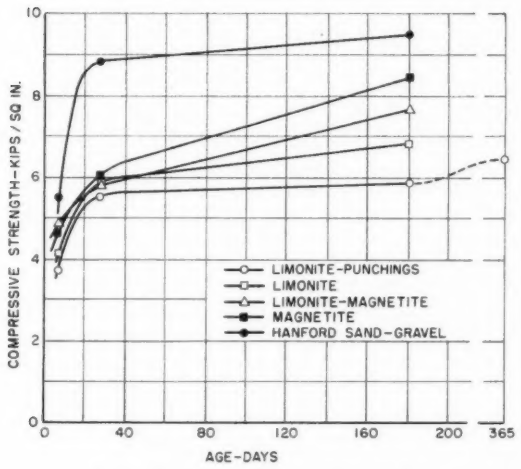


FIG. 2. COMPRESSIVE STRENGTH VS. AGE

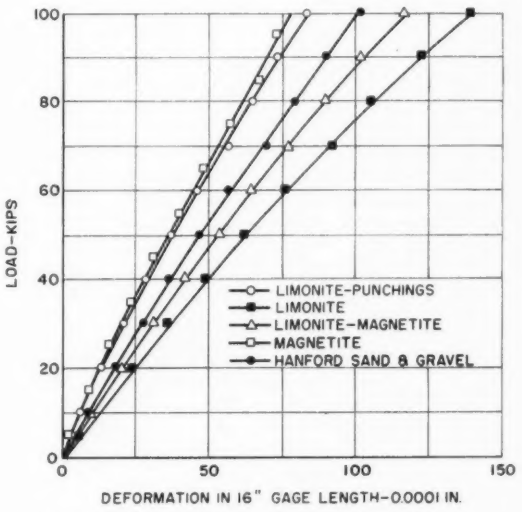


FIG 3. LOAD DEFORMATION FOR 28-DAY CYLINDERS

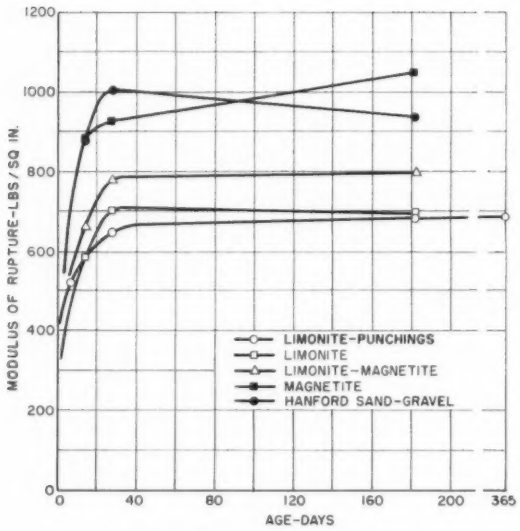


FIG. 4. MODULUS OF RUPTURE VS. AGE

high compressive strength also have high flexural strength.

Bond Test

The bond test on the concretes was conducted in accordance with standard procedure. The bond test was performed by imbedding a ¾-in. diameter reinforcing bar in a 9-in. cube. The bar was placed so that it projected through the concrete. The slip of the bar at both its loaded and unloaded end was recorded as a load was applied to the bar. The test was continued until the bar slipped excessively, or until the yield point of the steel was reached. In order to find the effect of placement of the bar at various depths of concrete, three different methods of placement were used. One bar was placed vertically in a 9-in. cube, one was placed horizontally at 4½ in. from the bottom of a 9- by 9- by 18-in. prism, and the third bar was placed horizontally at 4½ in. from the top of the prism. This prism, which was poured with a weakened section at midheight, at an age of about one week was broken to produce two cubes. The amount of water gain during placement of the concrete will affect the bond resistance, particularly for bars with considerable depth of concrete under them. This fact is recognized by the A. C. I. Building Regulations for Reinforced Concrete which permit a lower allowable bond stress for bars with more than 12 in. of concrete under the bar.

The results for the bond tests for the concrete at 28 days are shown in Figs. 5, 6, and 7. In these figures, vertical (V), top (T), and bottom (B) bars refer to the placement as just described. In Fig. 5, curves 1, 4, 7, and 10 are for vertically placed bars.

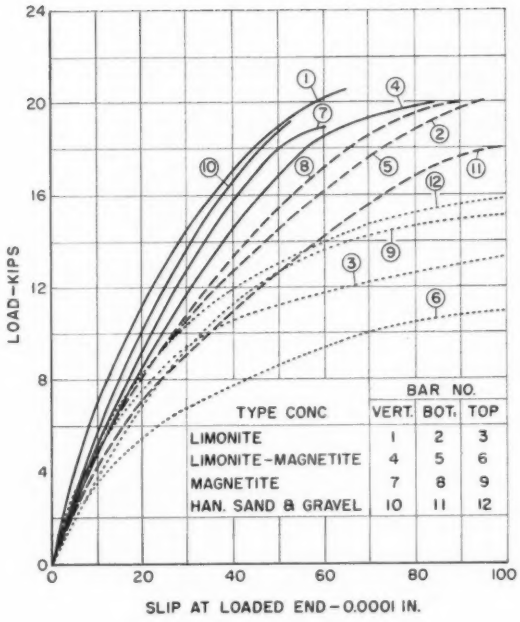


FIG. 5. BOND TEST AT 28 DAYS

These bars have the least slip at the loaded end. Bars 2, 5, 8, and 11 are bars placed horizontally with 4½ in. of concrete. These bars compose an intermediate group. The greatest slip is in the group of top bars: 3, 6, 9, and 12. Figures 6 and 7 present a comparison of slip at loaded and unloaded ends of the bars for average bond stresses of 300 and 600 psi. The slip at the loaded end of the bars for a bond stress of 300 psi was small, and the different mixes all produced about the same slip. The tendency for the top bars to have the least bond resistance was demonstrated. At 600-psi bond stress the tendency for top bars to slip excessively was evident. The slip at the unloaded end became large only when excessive slips occurred at the loaded end.

A comparison of the five concrete mixes and their effects upon the properties listed is given in Table II. The concrete made of Hanford sand and gravel was used for comparison. All results are for concrete specimens at 28 days of age.

Conclusions

Table II illustrates that the properties of concrete can be determined only from actual tests of concrete. The modulus of rupture of the concrete is almost inversely proportional to the water-cement ratio. The poor bond of the steel aggregate in the limonite-punchings concrete accounts for the deviation in this mix. The relative weakness of the limonite and magnetite mixes, apparent in the aggregate fractures

TABLE II

Comparison of Results With Various Concrete Mixes

Concrete Mixes	Limonite Punchings	Limonite	Limonite Magnetite	Magnetite	Hanford Sand & Gravel
Compressive Strength	63	66	66	68	100 (8870 psi)
Modulus of Rupture	64	70	78	92	100 (1005 psi)
Modulus of Elasticity	124	75	80	130	100 (5,710,000 psi)
Unit Elongation	127	107	107	47	100 (0.00015 in./in.
Slip at Loaded End—Vertical	135	100	129	125	100 (0.0024 in.)
Slip at Loaded End—Bottom	64	80	80	74	100 (0.0050 in.)
Slip at Loaded End—Top	77	234	341	106	100 (0.0047 in.)
Water-Cement Ratio	108	133	128	110	100 (0.366)
Inverse Water-Cement Ratio	92	75	78	91	100 (1/0.366)

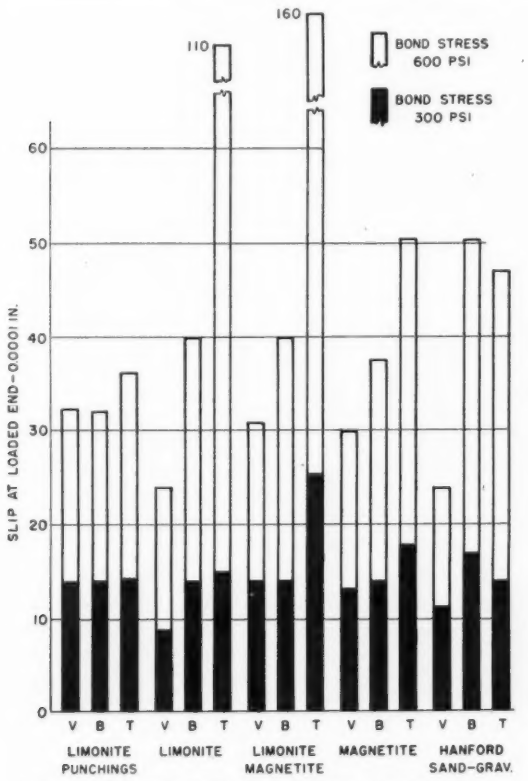


FIG. 6. COMPARATIVE SLIP OF BARS AT LOADED END FOR BOND STRESS AT 28 DAYS

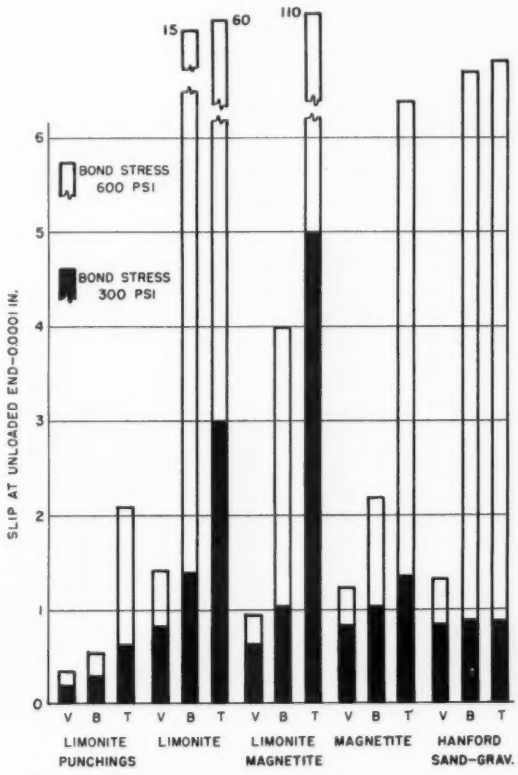


FIG. 7. COMPARATIVE SLIP OF BARS AT UNLOADED END FOR BOND STRESS AT 28 DAYS

of the compression tests, when compared to the Hanford sand-and-gravel control mix, was pronounced.

The use of large amounts of cement produced considerable expansion as measured by the expansion bar. This detrimental property will be somewhat offset by the increased resistance due to the higher strengths. The expansions are not unduly large when compared to those that might be expected if the concrete is subjected to a wide range of temperatures.

Another problem may be cracks produced by shrinkage of the concrete when it dries. The effects of such cracks upon resistance to radiation is not known.

In structural properties, these heavy-aggregate concretes all compare favorably with ordinary Portland cement concretes. If they prove to have the necessary shielding properties, they can be considered adequate for their purpose.

Experimental Stress Analysis as an Aid to Machine Design

EMMETT E. DAY
Associate Professor of Mechanical Engineering

E. E. Day

Design engineers must know how stresses are distributed in a loaded machine and how the materials behave under this loading. Analytical analysis, the usual basis of investigation of this distribution and behaviour, is either too cumbersome an approach for most practical problems, or, in many cases, is impossible, a fact which has resulted in the application of many empirical and rule-of-thumb relations and equations. With the development of the various techniques and equipment for experimental stress analysis, investigations of this kind of existing designs, or the gathering of information for future designs, have recently become routine and commonplace. Since many designers are not aware of the existence of such aids to their work, especially if they have been away from engineering institutions for even a few years, a brief review of most of the techniques may be worthwhile in order to point out the possibilities of the various methods. It is my intention to review only briefly these methods, trying to point out their possibilities and limitations. It should be emphasized, however, that their ultimate applications are bounded only by the scope of the engineer's imagination and ability.

Photoelasticity

Photoelasticity may be thought of as "seeing" stresses. Of course, this is not the case, but certain materials under stress become birefringent and transmit light on two perpendicular planes in a way which is proportional to the stress intensities on these two planes. In a polariscope this birefringent effect permits the stress distribution to be seen. Photoelasticity, unlike most other methods of stress measurement, is capable of giving the stress at a point; in other words, it is a strain gage of infinitesimal length.* This particular characteristic makes photoelasticity unparalleled for the determination of stress concentrations and stresses at irregular boundaries. Since most of these problems are not easily solved by analytical means, a complicated or impossible solution is reduced to one of simple arithmetic, with results that can be applied directly to design procedures. Most tables available for stress concentration factors have been determined in this fashion.

With the development of new plastic materials, three-dimensional photoelasticity has received added impetus. Fosterite is now available in large sections and shows promise of being the best material for the application of the frozen stress technique. This involves carrying the model through an annealing cycle while under load, with the result, that, because of the bi-phase properties of the material, the birefringent effect associated with the load is retained after the material has cooled and the load removed. The model is then sliced conveniently, and the problem reduced to one of two dimensions. Some other new plastics are showing promise of fabrication for large or complicated models, a technique hitherto impossible.

The introduction of bright flashing lights that may be triggered to fire with the movement of a machine member makes it practical even to study the stress state in models under dynamic loadings, or to make studies of shockloads. By stroboscopic control of flashing, it is possible to observe rapidly moving models either as if they were standing still or slowly traversing their cycle of loading.

Since this optical method renders results that are in close agreement with the theory of elasticity when the conditions are similar, we believe the results can be accepted with confidence where the theories are difficult to apply. Both these conditions are very vividly shown in Fig. 1. This is a simple cantilever beam loaded at the end. The photoelastic values and the theoretical results show very close agreement until the region of the fillet is reached. For some shapes of fillets, the theory could be extended to this region also, but the photoelastic method leads directly to quantitative results very readily showing the stress concentration present. The fillets would be neglected by application of the simple-beam theory.

With the development of Polaroid, equipment adequate for the solution of many design problems is now within the grasp of most organizations. Such equipment is no longer a novelty, and its frequent use will be rewarding. Fortunately, since photoelasticity has its limits and cannot be held up as a

* Brittle lacquer, which has a similar characteristic, will be discussed later.

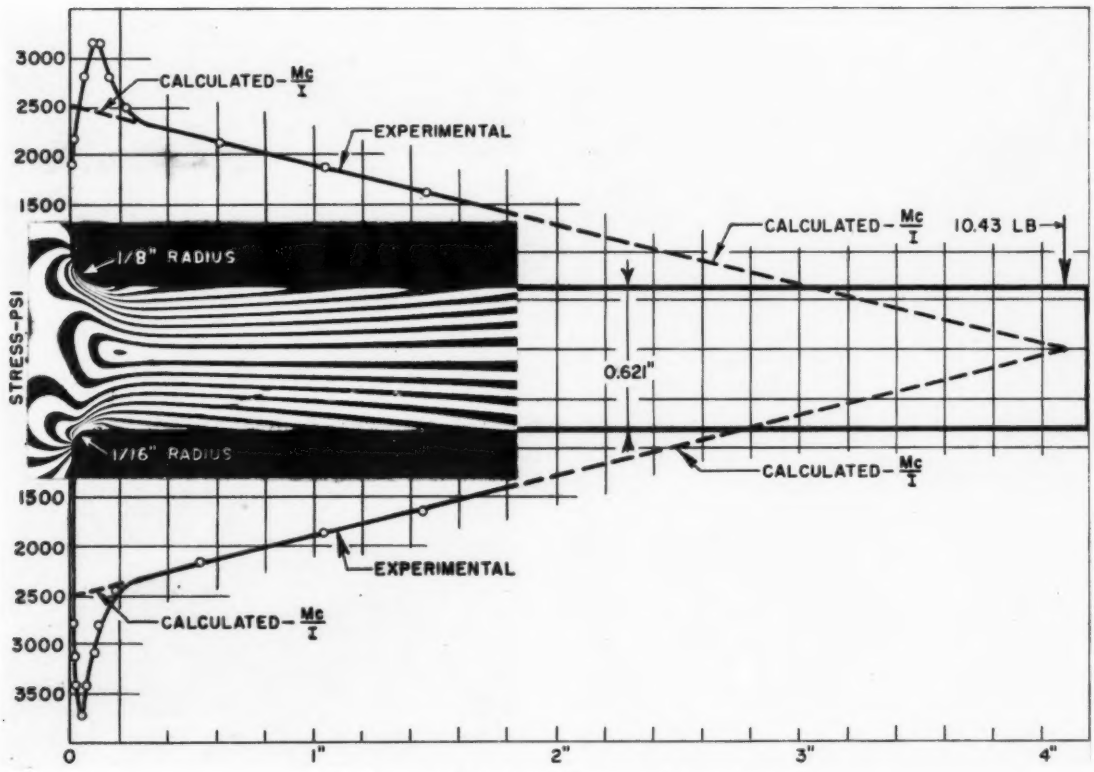


FIG. 1. CANTILEVR BEAM WITH DIFFERENT RADIUS FILLETS
(Note that the stress varies with the radius and is greatly in excess of that calculated by the beam theory.)

panacea for all design ills, other methods may take up where it is forced to leave off.

Brittle Lacquer

The development of brittle coatings has made possible the detection of strain and evaluation of stress in regions of machine members where no other method avails. Such brittle coating, manufactured and sold under the name, 'Stresscoat," is proving a powerful aid to design analysis.

This method consists of spraying the member in question with a lacquer which dries ready for use within a few hours, and will first crack at strains of 0.0005 to 0.001 inches per inch. This method of strain analysis in many respects is unsurpassed as an aid to designers because it covers the entire piece which is to be tested and, being non-destructive, allows the piece in use to be examined. Further, it shows strains at a point, thus giving a strain gage of infinitesimal gage length but complete in its coverage. Since it responds to elastic strains, it can be used in quantitative analysis and may be applied to the same machine many times for various phases of study, and it is exceptional in showing immediately the directions and regions of highest stress and stress concentrations, pointing them out for special study by other means. Regular Stresscoat is temperature sensitive and is for use in ordinary ranges. However, a ceramic brittle coating is now available which is good for ranges of —50 to +600° F. Its coatings range in sensitivities from 0.0004 to 0.003 inches per inch. Ceramic coating opens up a whole new realm of study for steel. A coating suitable for aluminum is also under development. The history of the successful application of brittle coatings for improvement of design, both from the standpoint of economy and performance, reads like a Horatio Alger story. The future will tell an even more fascinating tale about this technique, as design engineers become aware of its potentialities. Figure 2 shows the application of Stresscoat to the investigation of the strains due to loading of an irregular-shaped pipe wrench. Analytically unapproachable points of stress concentration, immediately located, can now be investigated by other, more precise means.

Strain-Gage Method

There is little new about the measurement of strain for stress analysis except that the instruments used are more accurate and versatile than ever known be-

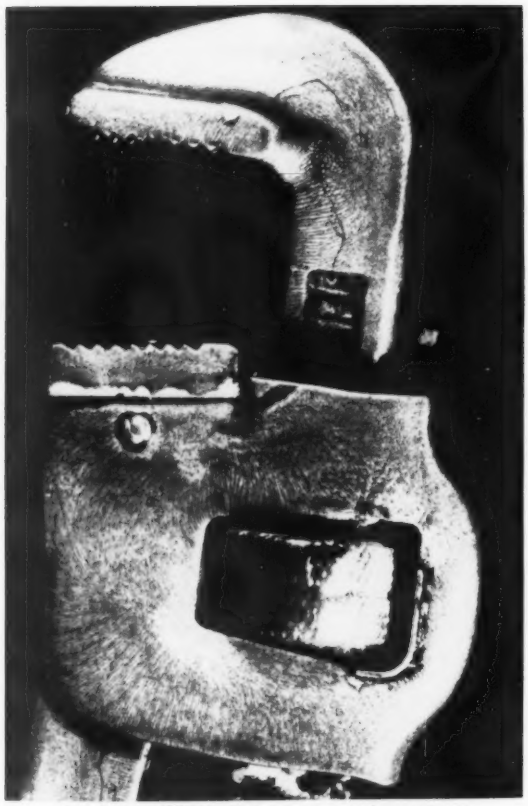


FIG. 2. PIPE-WRENCH STUDY WITH STRESSCOAT
(The wrench was subjected to 12,500 inch-pounds of torque to develop the pattern shown.)

fore. This versatility is attributed primarily to the development of the bonded resistance-wire strain gage. The literature so amply covers the applications of, and the instrumentation for resistance-wire gages that details of their use will not be considered here. Many books are available on the subject, and the design engineer who is coping with any problem of stress and/or behavior of machine members or materials must immediately inform himself by use of this wide variety of literature. The *Proceedings for the Society for Experimental Stress Analysis* is the best source to begin such a study.

The commercially available bonded type resistance-wire strain gages are of two main types: that for static measurement and that for dynamic measurement. For temporary application, these types are made with a paper backing; for more permanent application, they are constructed with a bakelite backing. Those of paper are suitable for temperatures of —200° to about +150° F., while the bakelite gages go to temperatures as high as 400° F. Gages vary in

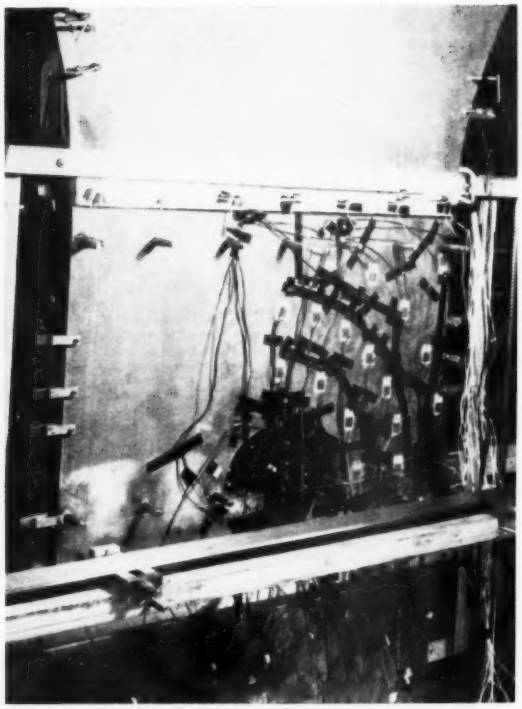


FIG. 3. BONDED WIRE STRAIN-GAGE STUDY OF A STRESS FIELD TO AID IN DESIGNING A SHIP PLATE

length from $\frac{1}{16}$ in. to 6 in. and are in many geometric shapes. Figure 3 shows the application of these gages to investigation of a stress field in a ship plate to arrive at a better design. It is only through knowledge of the exact conditions that prevail when a member is performing the duty for which it was designed that a true evaluation of the design can be made. These gages can make powerful contributions to that knowledge. Strain within a few microinches is measurable with the bonded type of gages as well as with the unbonded type which also utilize the change in resistance of a strained grid. Unbonded gages are useful in many applications where time for applying a bonded type is not available.

Other Types of Strain Gages

Strain gages which are purely mechanical or optical in nature are very useful where weight, shock, or dynamic loadings are not present. Of those of purely mechanical nature mention is made of the Huggenburger, Moore, and Berry gages where extreme accuracy of strain measurement is not desired. Those of optical nature are the Tuckerman, Martens, and the interferometer type of strain gage. These are extremely accurate, but require a great deal of technique and care in their application and use. Strain

measuring must be seriously considered by the design engineer if he desires to make the most of powerful techniques that have been developed for his use.

Other Methods of Experimental Analysis

Some equations are fundamental in the analysis of many unrelated physical phenomena. This results in the similarity of the differential equations describing the various systems, a similarity which enables one often to set up simple measurable models to simulate the behavior of very complex and unmeasurable phenomena, or to visualize the complicated system from a familiarity with the simple analogy. This analog method offers a direct experimental means for the solution of the torsion problem for irregular cross sections; for the finding of the sum of the principal stresses in a piece under load; for temperature distribution; and for other phenomena.* The measurement of a stretched membrane can be used to solve these equations usually with much less work and expense than attacking the problem analytically.

The design engineer who once makes use of experimental stress analysis to solve difficult stress problems will not be surprised to see it develop into a major tool for design investigation.

* Space here does not permit coverage of these methods, but full explanation of them can be found in the *Handbook for Experimental Stress Analysis*, edited by H. Hetenyi and published by John Wiley & Sons, or other related literature.

Northwest Chromites Show Promising Refractory Properties

A BULLETIN on the "Refractory Properties of Pacific Northwest Chromites," published as Report of Investigations No. 4299, was released by the U. S. Bureau of Mines in December, 1952. Authors are H. J. Kelly, Metallurgical Engineer, U. S. Bureau of Mines, N. W. Experiment Station, and Lecturer in the School of Mineral Engineering; K. G. Skinner, Ceramics Engineer, U. S. Bureau of Mines, formerly of the N. W. Experiment Station; and two former research fellows in the School of Mineral Engineering: M. E. Tyrrell and A. W. Goring. Work on the paper was done under a cooperative agreement between the U. S. Bureau of Mines and the School of Mineral Engineering of the University of Washington.

The investigation of the refractory properties of seven Pacific Northwest chrome ores and concentrates showed that five of the ores and one of the concentrates are suitable for making refractories and that all may be used in combination with high-grade chromite.

The specific objectives of the investigation were to determine the inherent physical and chemical characteristics, to prepare dense refractory shapes using each of the chrome ores and concentrates, and to compare the refractory qualities of the laboratory-prepared shapes with commercial chrome refractories. As far as possible, standard tests were used as criteria.

Samples of two chromite concentrates, Krome Corporation from Oregon and Benbow from Montana, and five chrome ores, High Plateau and Tyson from California, and John Day, Iron King, and Oregon Chrome from Oregon were studied. Pyrometric cone equivalents of all were over 40 (1,885° C).

By proper grain-size proportioning, high-forming pressures, and high-firing temperatures, dense refractory shapes were produced. Bricks made of equal parts of 14- to 48-mesh and through 100-mesh fractions of Benbow, Mont., concentrates, formed at a pressure of 11,000 psi and fired to cone 30 (1,650° C), had a bulk density of 219.83 pounds per cubic foot and an apparent porosity of 12.48 per cent. High Plateau chrome ore in proportions of 50 per cent 4- to 10-mesh, 20 per cent 20- to 35-mesh, and 30 per cent through 65-mesh material, formed at 11,000 psi and fired at cone 30, had a bulk density of 228.12 pounds per cubic foot and a porosity of 9.00 per cent. The three fired commercial brick tested had an average bulk density of 190.5 pounds per cubic foot and an average porosity of 19.68 per cent.

Standard refractory tests of brick made in the laboratory and compared with commercially made chrome refractories showed the following results:

1. Brick made of Pacific Northwest chromite ores and concentrates had a greater density and lower porosity than commercial brick.
2. High-temperature load resistance of the brick made from Pacific Northwest chrome ore was higher than the commercial-burned refractories.
3. Pacific Northwest chrome brick had a somewhat lower bursting expansion due to iron-oxide absorption than that of the commercially burned brick tested.
4. Laboratory brick compared favorably with commercially burned brick in resistance to slump at high temperatures.

(Continued on page 32)

SHEARING STRENGTH TESTS OF GLUED JOINTS

S. SERGEV

Professor of Engineering Mechanics

S. Sergev

In the early years of the last decade, steel was on the high priority list and, as a result, engineers began to use timber more widely than before. Attention was therefore directed to glued joints in timber trusses as a substitute for split rings. Information on the strength of glued surfaces in composite wood I-girders was also needed. To answer these questions, Mr. Chester Hogue, then Director of the West Coast Lumbermen's Association, agreed to furnish the necessary test specimens and the writer, with the generous assistance of Mr. Harvey Johnson, made the tests at the University of Washington. Recent inquiries indicating interest in the results of these tests, which were not published at the time,* have prompted this brief account given with the permission of Mr. T. K. May, Director of Technical Service of the West Coast Lumbermen's Association.

Preparation of Specimens

The material used was "C" clear, unselected Douglas fir (Coast region) with a moisture content between 15 and 20 per cent. A moisture-resistant casein glue, and a phenol resin glue, both with gluing pressures of approximately 50 psi, were used. This pressure was obtained by tightening a one-half inch steel bolt with washers, situated in the center of the glued surfaces. Gluing was about a month old at the time of the tests.

Specimens were prepared as follows: Two outside pieces of 2-in. nominal thickness and varying widths, and one inside piece of 2-in. nominal thickness and 5½-in. width were glued together. Thus, the outside pieces had one glued surface and the inside piece, two glued surfaces. The glued area was 30 sq in. on each side, making a total of 60 sq in. Grain in the outside pieces was parallel and grain of the inside pieces was oriented to give different angles, θ, between grain of the inside piece to the grain of the outside pieces. Figure 1(a) shows a typical joint, indicating the load and angle, θ. Bolts were removed prior to testing.

* September, 1942.

Testing Procedure

These tests were considered pilot tests in strength of glued joints; consequently, no readings were taken of relative movement of the pieces. To get statistical averages of each type of joint, six specimens were prepared for each value of θ, except for $\theta=0°$ with casein glue, for which twelve specimens were prepared. The range of angle θ for both casein and resin glues was $\theta=0°$, 22.5°, 45°, 52.5°, 60°, 67.5° and 90°.

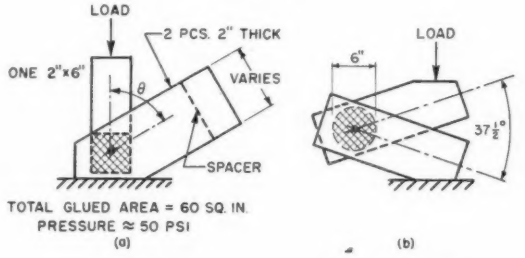
During the test two values of the loading were recorded: the loading at the first sound of distress and that at failure. The application of loading was slow and constant. After failure, the pieces were separated and the mode of failure observed and recorded under "remarks." Typical observations were as follows: failure of glue, one side; failure of glue on both sides, partially on glue surface; failure in wood, one side. The average values of stress at failure for different values of the angle θ are indicated in Fig. 2.

Another series of tests was designed to measure stresses of glued surfaces under torsion. The setup is shown in Fig. 1-b. The diameter of the glued surfaces was 6 in., with a ½-in bolt through the center. This bolt was not removed during the tests.

Discussion of Results

Although these tests were not exhaustive, the following conclusions and remarks seem justified.

FIGURE 1



Typical Joint — Joints in Torsion

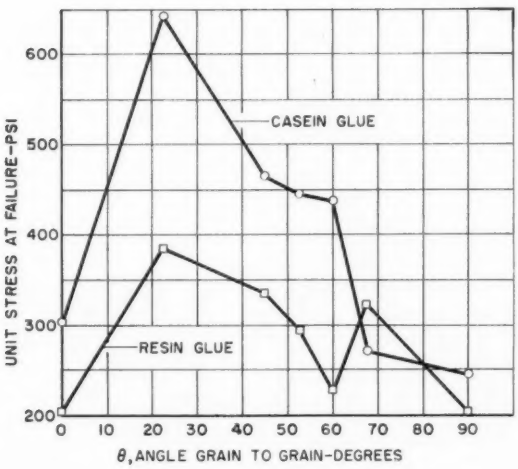


FIG. 2. STRENGTH OF GLUED JOINTS AT FAILURE

The joints with casein glue were, in general, stronger than joints with resin glue, possibly because of better penetration of the casein glue into the wood under the 50-psi gluing pressure. Casein glue is applied cold while resin glue is applied hot, the latter requiring a greater gluing pressure for successful bonding.

The two curves (Fig. 2) are similar and indicate low strengths at $\theta=0°$ and $\theta=90°$. Since the properties of the glue can be assumed constant, the latter results indicate that the strength of the joints may be determined by the wood. Both casein and resin joints indicate an optimum strength between $\theta=0°$ and $\theta=45°$, indicating that glued joints will be stronger if the grains of the pieces glued together are not parallel or perpendicular to each other. Results for the strength of resin joints for $\theta=60°$ for some reason were erratic, and the point plotted represents the average of the three highest values. But, since even these values were not of the same order of magnitude, the extreme low value on the graph may be discounted. A glance at the graph shows a gap in the information between $\theta=0°$ and $\theta=22\frac{1}{2}°$. It is obvious that no one anticipated that this region where wood is glued together with the grains parallel would require special attention. These tests also indicate that the strength of glued joints with grains perpendicular and that of joints with grains parallel to each other is approximately the same.

The strength of glued joints in torsion may quite possibly be affected by the initial angle relation of grain-to-grain. This is due to the fact that the bolts, although not removed during the test, fitted loosely and thus did not serve as axes of rotation. Thus we conclude that direct shear was present, and orientation of grain-to-grain would influence this strength. The torsional effect would utilize the strengths from $\theta=0°$ to $\theta=90°$, the shearing stress acting on the grains at all angles from 0° to 90° but being functions of the original angle $\theta=37\frac{1}{2}°$ in the case under consideration. It may be safe to conclude, from the results shown in Fig. 2, that torsional resistance of glued joints will be smallest when the pieces are glued together with grains parallel or perpendicular to each other. The maximum average stress at failure for casein joints based on the formula:

$$S_s=\frac{P}{A}+\frac{M_t r}{I_p},$$

is 810 psi, and that due to torsion alone is 650 psi. For the resin-glued joints, the corresponding values are 485 psi and 390 psi.

The load at which the first sound of distress was heard varied, but in general was approximately one-half of the load at failure for all joints.

HARDBOARD PANELS FOR SOUND ABSORPTION AT LOW FREQUENCIES

(Continued from page 12)

Curved panels are noticeably superior to flat and splayed panels, especially with the addition of an absorbent backing.

The work done to date on this project shows, as was anticipated, that there is considerable similarity in acoustic properties of resonant panels whether made of hardboard or plywood, and also that unexpected variations may appear with any panel. If resonant absorbers such as these are to be used for accurate treatment of audio rooms, it seems desirable to use only types of panels which have been previously tested.

It is obvious that there are a large number of combinations of thickness, material, shape, and acoustical treatment that may be incorporated into the design of such panels. The tests made to date have been of materials commonly used in panel design, in shapes that are easily used in acoustical treatments. Additional tests are in progress.

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THE EFFECT OF DIELECTRIC HEATING ON CATALYST ACTIVITY*

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The dielectric heating of catalysts has many advantages over other methods because of the uniform temperatures produced and the ease of control. Because of the more rapid molecular motion in a high-frequency field, it would be expected that this method of heating should affect catalyst activity. The purpose of this investigation was to evaluate the magnitude of this effect.

Literature Survey

The literature survey has revealed only a few articles pertaining directly to the effect of a high-frequency alternating electric field on heterogeneous catalysts. Komarewsky[1] reported that a 90 per cent yield was obtained in the dehydration of ethyl alcohol over alumina at 350° C and a space velocity of 0.5. The yield in the dehydrocyclization of heptane to toluene over a chromia-alumina catalyst was 75 per cent at 500° C and space velocity of 0.5. These data were not compared with yields from ordinary heating. In discussing the process, Komarewsky[1] points out that dielectric heating eliminates overheating in spots and thus minimizes side reactions, increases the life of the catalyst, and gives a more uniform product. Since the temperature is obtained rapidly (3 to 5 minutes), the processing time and size of chamber may be decreased and the space velocity increased. The possibility of using dielectric heating with "fluidized" catalysis is mentioned. Brathovski[2] found that intense exposure of platinum solutions to ultra high frequency fields decreases the catalytic effect of the platinum on hydrogen peroxide decomposition, whereas moderate exposure increases the catalytic effect. Similar studies were made earlier by Wilke and Gauser.[3] Generalizing on the type of catalyst and its effect, they concluded that a definite relation exists between the action of the field and the colloidal state of the catalyst. Several patents have been obtained for methods using different kinds of catalyst for different types of reaction, e.g., rutile or brookite as a polymerization promoter for organic compounds of high dielectric value,[4] barium carbide (BaC_2) for the manufacture of ammonia from nitrogen and hydrogen,[5] and others.[6,7,8]

R. W. Moulton

In the laboratories of the University of Washington[9] the alternating field in phenol-formaldehyde condensation and ethyl actetate hydrolysis with acid-base catalysis was found to cause a rise in reaction rates corresponding to 1° to 4° C higher temperature with conductive heating. The greater the high-frequency power input, the greater was the observed increase in the rate of reaction.

In a recent United States patent[10] a magnetic field is used to control the activity of heterogeneous catalysts. As an example, nickel on asbestos for use in hydrogenating cotton-seed oil, or iron oxide on asbestos in oxidizing toluene to benzaldehyde, is subjected to the action of a substantially constant uniform magnetic field of strength 5 to 10 gauss where a retarding effect is desired, and a strength below 5 gauss where an accelerating effect is desired. Since the magnetic fields are said to orient the molecules of a substance in a regular manner, changes in catalytic properties may well be a result of this orientation.

Preliminary Experiments and Results

After surveying the field of common vapor-phase reactions, it was decided to use the conversion of acetic acid to acetone over an alumina catalyst. This reaction proceeds according to the following equation:

$$2\,CH_3\,COOH \xrightarrow[\text{Catalyst}]{Al_2O_3} CH_3\,COCH_3 + CO_2 + H_2O.$$

The reaction has been reported to occur from 275° to 500° C with various oxide catalysts. Alumina was

* Condensed by N. R. Mukherjee from the M.S. Thesis in Chemical Engineering submitted by F. N. Grimsby, 1949.

chosen from these catalysts since it consists of only one component (Al_2O_3) and, because of its application both as a catalyst and a catalyst support in a number of reactions, its electrical property would be of more general interest than that of the other catalysts. Two forms of alumina were used in this experiment: one prepared from aluminum isopropoxide* by the method of Adkins and Hissen,[11] and the other obtained as anodized alumina by the method of Taylor *et al.*[12,13] The literature does not mention the latter form of alumina as being a catalyst for the chosen reaction.

An apparatus was constructed for the preliminary investigation of the catalyst activity. In this apparatus the acetic acid was fed by mercury displacement to an electrically heated oil bath where it was vaporized. The reaction tube consisted of two pyrex glass tubes heated by the coils of an electric furnace. The acid vapor was heated in the outer tube and then passed over the catalyst inside the 13-mm o.d. inner tube. The gases leaving the reaction zone flowed countercurrent to the incoming vapor, thus permitting heat exchange. The cooled vapor was first condensed by a water condenser and then cooled by an ice bath. The uncondensed gas (carbon dioxide) was passed through a dry-ice trap and a water scrubber to remove the residual organic vapors. The gas was then dried through a U-tube of "Anhydrone," and the carbon dioxide was absorbed in a U-tube of "Ascarite" (plus some "Anhydrone" to absorb water formed during carbon dioxide absorption).

In the initial investigation the isopropoxide catalyst was used in pill form. Thirteen pills† occupying a zone of about 4 cc in the reactor, were dehydrated by heating at 400° C for one hour. (The dehydration temperature in making the alumina catalysts is somewhat limited.[14]) For the three runs made at different temperatures, the degree of conversion of acetic acid to acetone is given in Table I.

Several runs were made over a freshly anodized surface at 465° C, 470° C, 500° C, etc. The results indicate only a small activity of anodized catalyst for the desired reaction and a tendency towards cracking reaction, producing methane.

To compare the crystal structures of the anodized and isopropoxide aluminas, X-ray powder-diffraction patterns were obtained. The pictures failed to show a definite pattern for the isopropoxide catalyst, but the anodized sample showed definite lines corresponding to various crystal modifications of alumina.

Attention was again turned toward the isopropoxide catalyst, this time to examine the possibility of forming a coating of the catalyst on an aluminum

TABLE I

Effect of Temperature on the Conversion of Acetic Acid

(With isopropoxide catalyst in pill form)

Run No.	Temperature (° C)	Liquid Feed Rate (cc/hr)	Conversion of Acetic Acid (%)
1	465	17.9	37
2	426	16.1	13
3	382	18.0	3

electrode. The surface of an aluminum plate was roughened by pressing it against the surface of a rough file in a vise, followed by etching in 10 per cent hydrochloric acid at 40° C to give a mossy appearance under a microscope. The two-inch wide sheet was then rolled into a spiral that would fit into the reactor tube. The coating was applied by dipping the spiraled strip into molten aluminum isopropoxide. When the surface had hardened it was exposed to moist air for several days. A jet of air was then played on the white coating in order to remove all that was not held tightly (80 per cent adhered to the surface). In this way an area of 7.2 sq in. was coated with a layer of hydroxide equivalent to 0.383 gm of Al_2O_3.

Two runs were made with this catalyst. The first run gave a conversion of 34.5 per cent at a feed rate of 18.1 cc per hour of acetic acid and temperature of 468° C. In the second run, at a feed rate of 41.7 cc per hour, a conversion of 20.8 per cent was obtained at 464° C. The data of these runs were utilized in the evaluation of the constants of the equation,

$$C = mR^3 + nR^2 + oR + p,$$

where C=cc of acid converted per hour; R=feed rate of acid, in cc per hour; and m, n, o, and p are constants. On evaluation of the constants the following equation was obtained:

$$C = 0.000801\ R^3 - 0.0573\ R^2 + R.$$

From this equation, the point where

$$\left(\frac{dC}{C}\right) \Big/ \left(\frac{dR}{R}\right) = \frac{0.001}{0.10}$$

was found to be at R=43.3. This is the point where 10 per cent variation in feed rate gives only 0.1 per cent in the product yield. Therefore, operation in this region would allow for some fluctuation in the feed rate.

If diffusion is not the controlling factor of the reaction, as is likely to be the case at high vapor velocities and high reactant concentration (i.e., low conversion) and if the catalyst layer is thin, the reaction may be treated as a homogeneous gas reaction. By using equations given by Hougen and

* For brevity this catalyst will be referred to loosely as "isopropoxide catalyst."

† Each pill consisted of 0.8 gm $Al(OH)_3$.

TABLE II

RATE CONSTANTS OF THE REACTION

FEED RATE (cc/hr)	TEMP (°C)	CONVERSION (%)	RATE CONSTANTS Mols/(hr)(cc)(atm²)
18.1	468	34.5	0.0462
41.7	464	20.8	0.0490

Watson,[15] the reaction velocity constants were calculated from the previous two runs. Results are given in Table II.

Even when a temperature correction is made, these constants are in fairly close agreement for data of this type, thereby supporting the validity of the foregoing assumptions.

All the above calculations are based on a minimum of data and were intended to serve only as a guide in designing a reactor. They should not be used without recognizing their limited nature.

Reactor and Experiments

A sketch of the reactor with auxiliaries, as designed on the basis of the preliminary experimental data, is shown in Fig. 1. Each of the two electrodes consisted of twelve disks cut from a ⅛-in. by 25-in. aluminum plate. The disks were supported on 3/16-in. aluminum tubing and spaced by ⅜-in. long spacers cut from ¼-in. aluminum tubing. The disks were cut to fit into the 32-mm o.d. reactor tube with a 0.015-in. clearance on the diameter to allow for the difference in thermal expansion of aluminum and of pyrex glass, of which the reactor tube was made. The procedure for coating the electrodes with the isopropoxide catalyst was the same as already described except that this time the disks were roughened by cutting a knurled surface on a shaper. This permitted the formation of a somewhat heavier, more firmly held coating. Two iron-Constantan thermocouples, with their junction space 4½-in. apart, were placed inside the tubing of the grounded electrode. Except for the 6-in. space occupied by the catalyst-coated electrodes, the 24-in. pyrex reactor tube was filled with pyrex Raschig rings. High-frequency power was supplied by a 1-kw output Westinghouse Industrial RF Generator described fully by Buckham and Stuelpnagel[16] and Schuyten[17] in connection with their studies of the dielectric properties of aluminum. External heat was supplied by two resistance-furnace cores, one for vaporization and preheating and the other for maintaining constant temperature of the reaction zone. Each was insulated by magnesia insulation and separately controlled by Variac variable voltage transformers.

The 99.5 per cent acetic acid (glacial, Merck) was fed from the constant head apparatus to the reactor through the feed-rate controlling capillary tube. The

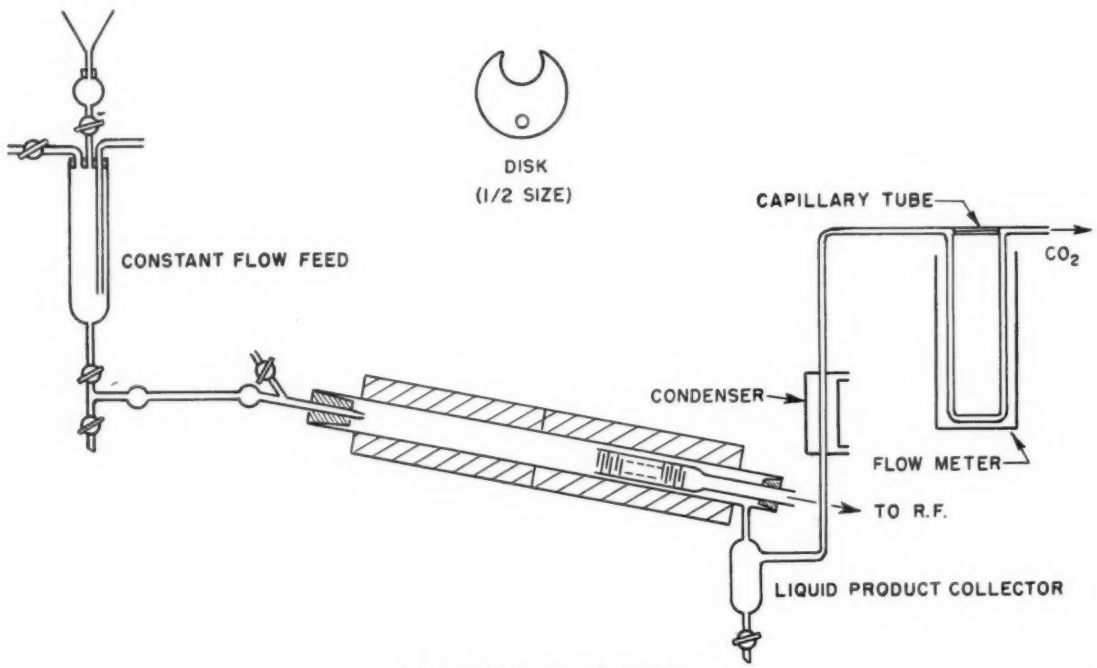

FIG. 1. REACTOR WITH AUXILIARIES

liquid component of the stream leaving the apparatus accumulated in the "liquid-product collector," while the non-condensables passed through the Friedrich's Condenser to the flowmeter. Nitrogen was used to sweep the air from the apparatus before feeding the acid and also, in shutting down, to remove the organic vapors in order to prevent condensation in the reactor.

Results

Certain restrictions limited the study of factors varying in a wide range. However, the results of the runs made in the designed reactor, as shown in Table III, do not give evidence that the high-frequency field affects the catalyst activity.

Discussion and Conclusions

The flow rate on the manometer, showed no immediate change upon application of the high-frequency field, i.e., there was always a lag of several minutes before the increase in rate was prominent. This indicated that the rate increase was due to the heating of the reactor, because any effect from the field alone would be instantaneous.

The data presented here should not be considered conclusive, since further experimentation is necessary. A greater amount of fringing, coupled with its high dielectric loss at temperatures above 300° C, made pyrex glass unsuitable for this investigation. Fused silica glass, phosphate glass, and concentric aluminum tubes, from their characteristic properties, would seem to be possible construction materials.

Of the two forms of alumina catalyst, isopropoxide catalyst proved excellent for this reaction. The dielectric loss of the isopropoxide catalyst was negligible, so far as heating in the designed reactor was concerned. Second order rate constants calculated for a homogeneous gas reaction gave fairly good correlation of the preliminary data.

TABLE III

RESULTS OF RUNS MADE WITH VARYING FIELDS

FIELD	VOLTAGE	TEMP RISE IN 38 MIN (°C)	MEAN TEMP (°C)	CONVERSION (%)	CONVERSION CORRECT. TO 389° C (%)
R.F. . . .	300	34	389	3.10	3.10
D.C. . . .	300	34	385	3.00	3.59
None . . .	. . .	34	396	3.66	2.57

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REPORT BY UNIVERSITY AERONAUTICAL ENGINEERS IS RELEASED BY NACA

Technical Note 2895, "Effect of Variable Viscosity and Thermal Conductivity on High-Speed Slip Flow Between Concentric Cylinders," was issued in February by the National Advisory Committee for Aeronautics, who sponsored the work. Authors are T. C. Lin, Junior Research Engineer, and R. E. Street, Associate Professor, both of the Department of Aeronautical Engineering.

The report presents the following summary:

"Schamberg was the first to solve the differential equations of slip flow, including the Burnett terms, for concentric circular cylinders assuming constant coefficients of viscosity and thermal conductivity. The problem is solved for variable coefficients of viscosity and thermal conductivity in this paper by applying a transformation which leads to an iteration method. Starting with the solution for constant coefficients, this method enables one to approximate the solution for variable coefficients very closely after one or two steps. Satisfactory results are shown to follow from Schamberg's solution by using his values of the constant coefficients multiplied by a constant factor η, leading to what are denoted as the effective coefficients of viscosity and thermal conductivity."

This research is an extension of the previous work of Dr. Lin which was sponsored by the Engineering Experiment Station and published in Bulletin No. 118.

Sixth Annual Conference on Road Building Held at Corvallis*

R. G. HENNES

Professor of Civil Engineering

Left to Right: **J. L. Gray, Instructor in General Engineering, and M. P. Coopey, Professor of Highway Engineering, both of Oregon State College**

THE SIXTH ANNUAL CONFERENCE on Road Building was held at Oregon State College, Corvallis, on February 26-27, 1953, with registration exceeding 180. This meeting is the outgrowth of previous meetings held under the same name at the University of Washington since 1948, combined with the Oregon State Conferences on Roads and Streets which have been meeting at Corvallis since 1949. The combined conference meets on alternate years at each institution.

Some effects of the cooperative staging of the Road Building Conference are to be found in better programs, broader recognition, and a more intimate association of Northwestern road builders.

This year's conference was arranged under the chairmanship of Martin P. Coopey, Professor of Highway Engineering at Oregon State College, assisted by Mr. James L. Gray, engineering instructor in the same institution. In his development of a technical program Professor Coopey was aided by an advisory committee which includes state, county and city representation from both Oregon and Washington. The Washington representatives include the membership of the Washington State Council for Highway Research.

The delegates were welcomed at the Thursday morning session by Dean George W. Gleeson, who discussed the growing magnitude of the highway transportation problem. It is relevant to note that the American public spends more on automobile insurance than on the roads and streets which carry the automobile.

Mineral aggregates were discussed in two papers by members of the Oregon State Highway Department. Mr. G. W. Harra, Materials Engineer, described the necessity for careful specifications for aggregate. Mr. Lewis E. Scott, Geologist, told where and how suitable aggregate deposits were located. Mr. Roy C. Edgerton, Research Engineer for the Oregon Highway Department, described recent concrete bridges in both Oregon and Washington, and discussed the place of prestressed concrete in highway bridge design.

On Thursday afternoon "Street Lighting" was the subject of a paper by Stacy Standley of the Line Materials Company. Mr. Standley believes that incandescent, fluorescent and mercury vapor lighting are useful under appropriate conditions. An important factor is the height of the light source.

A very interesting pair of papers on the applications of hydrology and hydraulics to bridge design were presented by two Tacoma engineers with the U. S. Geological Survey, Mr. F. M. Veatch and Mr. G. L. Bodhaine. The resources of this organization in providing information regarding probable flood flows for any specific Northwest stream are being ever more widely utilized by county and state engineers. Subsequent talks by two of the Oregon State College staff, R. H. Shoemaker and L. A. Clayton, served to explain the use of hydraulic models in drainage problems, and to suggest a more efficient design of box culverts than those used in present practice.

Left to Right: **R. G. Hennes, E. M. Horwood, civil engineering professors at the University of Washington, and O. L. King, City Manager, Eugene, Oregon**

* All photographs by courtesy of *Pacific Builder and Engineer.*

A trio of important papers on bituminous pavements were presented Friday morning. The recent use of asphaltic emulsion for the treatment of base courses was described by C. M. Wimberly of the American Bitumuls and Asphalt Company. The cost of this treatment is comparable to that of the conventional prime coat, and is often advantageous. Mr. Vaughn R. Smith, of the California Research Corporation, presented a thorough review of stability test methods used for asphalt paving mixtures. Of the several laboratory procedures in current use, he believes that the Hveem stabilometer is the best for routine laboratory work, while the conventional triaxial test is superior for basic research. Mr. F. N. Hveem, Materials and Research Engineer for the California Division of Highways, described the sand equivalent test developed under his direction. This test supplements or replaces mechanical analysis and Atterberg in the selection of aggregates. A measured quantity of the material is added to a special aqueous solution and allowed to settle. The volume of the resulting sediment shows the effect of its clay content on the performance of the aggregate. The simplicity of the test makes it very useful in field control.

Professor Edgar M. Horwood, University of Washington, presided at the closing session. A paper

Left to right: **A. S. Wellborn, Managing Engineer, Pacific Coast Division, Asphalt Institute, Vaughn Smith, California Research Corporation, and F. N. Hveem, Research Engineer, California Division of Highways**

Left to right: **L. E. Scott, Materials Engineer, and G. W. Harra, Geologist, both of the Oregon State Highway Department**

on the control of landslides was presented by Professor R. G. Hennes, also of the University of Washington. Landslide control is more effectively achieved by improving the strength characteristics of the soil than by attempts to reduce stress intensities. Soil-shearing resistance is improved when frictional forces are increased through reduction in hydrostatic uplift or when cohesion is increased by reduction in water content. In either case, drainage is the main recourse of the engineer. Successful drainage methods include ditch interceptors, vertical wells, horizontal wells, ventilating tunnels or shafts, and vacuum drainage.

The final paper was presented by Mr. Oren L. King, City Manager of Eugene, who illustrated his talk on public relations with a color film showing the municipal activities of an Oregon city.

Inquiries for copies of 1953 Conference Proceedings should be addressed to Professor Martin Coopey, Oregon State College, Corvallis. Proceedings for past years are still available at the Engineering Experiment Station, University of Washington.

COMPREHENSIVE REPORT ON TOLL ROADS FOR WASHINGTON

THE REPORT on "Feasibility of Toll Roads in Washington," prepared by Willa Wilcox Mylroie, Project Engineer, was presented by the Washington State Council for Highway Research, to the State Legislature at its recent regular session. The report was requested by the Washington State Highway Commission and the Joint Fact-Finding Committee on Highway, Streets and Bridges of the Legislature.

Part I presents a review of toll roads already in existence in this country, with special note of factors of location, administration, financing, and operation, to provide an experiential background for considering the Washington problem.

Part II discusses travel habits and their relation to toll roads. Part III outlines bases for forecasting future traffic in Washington, and tabulates predictions of population in Tri-County (King, Pierce, and Snohomish Counties) and the state of Washington for 1955, 1960, and 1965.

A financial comparison of toll roads with other roads, and a survey of potential toll-road locations in Washington comprise Parts IV and V. Specific attention is paid to the Puget Sound Turnpike and Cascade Tunnel as possible projects.

The report concludes with emphasis on the necessity of paralleling toll roads with free roads, and points out that a long view should be taken in planning any toll road, in order to meet conditions required by its ultimate transfer to the regular highway system.

Engineering Research Dividends

Recent theses submitted for advanced degrees from the College of Engineering, University of Washington, will regularly appear in abstract form in *The Trend*. Complete copies of these theses are available for reference at the University of Washington Library. Address inquiries to the Director of the Engineering Experiment Station, University of Washington, Seattle 5.

WALL, R. E. "A Method of Forming a Broad Band Microwave Frequency Spectrum." M. S. in Electrical Engineering, 1953.

A method of generating a wide spectrum of evenly spaced sidebands in the microwave region, suitable for use as a frequency standard, is presented and discussed. The frequency spectrum is produced by modulating the beam acceleration voltage of a klystron with two high-frequency voltages. The frequency of one of these modulation voltages is an integral multiple of the frequency of the other voltage so that certain sidebands of the lower frequency coincide with the sidebands of the higher frequency. The output of the klystron then consists of a frequency spectrum about the microwave-carrier frequency, with the spacing between sidebands equal to the lower of the two modulating frequencies. The method is examined analytically and experimentally. The operation of a klystron is ordinarily expressed with time as the variable. An analysis making use of the Laplace transform to convert the function of time into a function of frequency has been found convenient. The result gives the magnitude of the sidebands as a function of the operating parameters of the klystron.

SCHOLEN, D. E., "Hydraulic Jet Air Ejector for Ozonating Drinking Water." M.S. in C.E., 1952.

This study arose from the need for research on design methods and effectiveness of a hydraulic jet ejector to be used in the ozonation or oxidation of drinking water, sewage, or industrial wastes. The water-treatment plant at Philadelphia, using porous plates for ozonated air diffusers, has been effective in taste and odor control but inconsistent in killing coliform organisms. In the present study a greater contact efficiency was sought by pumping the water through an ejector with the ozonated air drawn in and mixed by the high velocity flow in the throat section. A contact period of from 10 to 30 minutes was provided, though its need has not been proved.

(Continued on page 32)

CHHABRA, S. P., "Quadrant-Shaped Cantilever Plate." M. S. in Aeronautical Engineering, 1952.

The problem of the quadrant-shaped cantilever plate clamped on the circular edge is investigated. An exact solution is found by the use of a power series representing the deflection function, and satisfying the geometric boundary conditions. The problem is further simplified by making the power series automatically satisfy one of the dynamic boundary conditions. Then analysis is carried out by separating the series into distinct groups, thereby simplifying the calculations. By superimposing the solutions for these individual cases, the final solution is obtained. The load corresponding to the final solution is of limited practical application because the choice of series puts restrictions on the deflected shape assumed by the plate. However, a modification of the series is suggested which could perhaps lead to useful load distributions. The load considered here is symmetrical about the line bisecting the quadrant, and is constant along all free edges of the plate.

PASTELL, D. L., "Electrolytic Titanium." M.S. in Chemical Engineering, 1947.

The preparation of titanium by chemical methods has been expensive and unsatisfactory because of its high melting point, its tendency to combine at high temperatures with oxygen, nitrogen, and carbon, and the ease with which it forms alloys with common metals. The purpose of this investigation was to study the possibilities of producing metallic titanium by electrolysis, limiting the present research to electrolysis of fused salt baths and non-aqueous solutions of titanium tetrachloride. The following results were obtained.

1. Electrolysis of solutions of titanium dioxide in molten calcium chloride under varying conditions of concentration, current density, and time of run gave a maximum conversion of 4.82 per cent. A carbon anode and stainless steel cathode were used.

(Continued on page 32)

Notes and Comments

ENGINEERS IN THE NEWS

F. N. GRIMSBY, junior author of the article on dielectric heating and catalyst activity in this issue, is now an instructor at M.I.T. and is doing graduate work toward a Ph.D. degree.

H. M. SWARM, Assistant Professor of Electrical Engineering, and **GLEN H. KEITEL,** who holds a G.E. fellowship in electrical engineering, read a paper on "Tropospheric Propagation in Horizontally Stratified Media over Rough Terrain," at the annual national meting of the IRE, in New York, March 23-26. This paper is an outgrowth of the M.S. thesis of **R. N. GHOSE,** former fellow in the E.E.S., whose experimental work on Project 1 was sponsored by the National Bureau of Standards. At a symposium on tropospheric propagation sponsored by the Naval Electronics Laboratory, March 30 to April 1 in San Diego, Professor Swarm also presented for discussion the paper "Field Strength Calculations over Rough Terrain," of which **W. A. LOWE** was co-author.

R. A. HECHTMAN, Associate Professor of Structural Research, attended the annual meeting of the Research Council on Riveted and Bolted Structural Joints, in Chicago February 12, 13, to present a progress report on the research of the past year on slip of structural steel double-lap bolted joints assembled with high tensile steel bolts.

F. D. ROBBINS, Assistant Professor of Electrical Engineering, attended the meeting in Seattle, March 9, of the Bonneville Regional Advisory Council of which he is a member. The Council discussed the power-shortage problem and ways and means of solving it, including use of power sources other than hydro, with special attention to the possibilities of steam plants. During the meeting the passage of the State Power Bill by the Legislature was announced. Problems of federal and state administration of power facilities were also discussed.

R. N. KUSIAN, Director of the Environmental Research Laboratory, attended the "Symposium on Hydrazine and Its Applications" held in Chicago, February 2, 3. Since the topic of discussion fell under classified material, attendance was by invitation to research agencies interested in rocket fuels.

A new book, entitled *Engineering Manufacturing Methods*, by **G. S. SCHALLER,** Professor of Mechanical Engineering, was recently issued by the McGraw-Hill Book Company. It covers the major aspects of engineering manufacture, such as founding, welding, machining, hot shaping, cold shaping, thermal treatment, and engineering materials.

SEATTLE ASCE HEARS ALCAN SPEAKER

The Seattle Section of the ASCE at its meeting on March 26 heard Franklin T. Matthais, Assistant Project Manager for Alcan's Vancouver office, speak on the power development and smelter phases of the Nechako-Kitimat project of the Aluminum Company of Canada, with slides illustrating the dam, tunnel, and powerhouse construction. The hydro project is stupendous, involving some 10 miles of tunnel through the Coast Range to develop a head of 2,850 feet and a power output exceeded only by Grand Coulee. The ultimate aluminum production capacity is to be about 65 per cent of present total U.S. Production.

Plans for the meeting of the Pacific Northwest Conference, May 1 and 2, include papers on the economics of transportation (Trans-Sound Bridge, Marine Facilities Development, and Air-Traffic Development), and on electric power, fuels, and industry.

The Vancouver Branch of the Engineering Institute of Canada will hold a joint meeting with the Seattle Section in Vancouver, May 23.

METAL WITH STRANGE PROPERTIES NEEDS MORE USES

It is more than two years since Alcoa, a major gallium producer, widely publicized gallium's properties, but only a few minor uses have developed for this mystery metal.

Gallium melts at about 86° F but doesn't boil until 3600° F or higher. Like water, it expands upon solidification. Its electrical resistivity variability is believed greater than that of any other metal. It emits electrons at extremely low temperatures. Chockfull of unique properties, gallium is truly one of the most unusual elements.

Exploiting the properties of gallium has been the problem. Some uses exist, but at over $1000 a pound we can count on our fingers the pounds used each year. It appears in dental alloys for gold restoration work. A patent has been issued for minor use in selenium rectifiers. Gallium chloride is used experimentally as a catalyst for polymerization of vinyl ethers. Radioactive gallium has been used in the diagnosis and treatment of bone cancer. The most promising application, though quantitatively minor, is as a liquid seal on the inlet system of mass spectrometers, where its liquid range and low vapor pressure make it superior to mercury in analyzing hydrocarbons with high boiling points.—*Alcoa Aluminum News-Letter*, February, 1953.

NEW REPRINTS

Reprint No. 70. "The Strength of Gravel in Direct Shear." R. G. Hennes, *Am. Soc. for Test. Mat.* STP No. 131, 1952.

Reprint No. 71. "Radio Influence from Power Transmission Lines — Effects of Wind, Dust, and Smoke." G. S. Smith, A. B. Jacobsen, *AIEE Trans.*, 1952.

Reprint No. 72. "Stability and Durability of Plant-Mix Macadam." J. R. Clanton, R. G. Hennes, *Highway Res. Bd. Proceed.* Dec., 1951.

Reprint No. 73. "Analogue Methods for Optimum Servo-Mechanism Design." F. C. Fickeisen, T. M. Stout, *AIEE Trans.*, 1952.

Reprint No. 74. "Early Freezing of Non-Air-Entraining Concrete." D. C. McNeese, *Jour. Am. Concrete Inst.*, Dec., 1952.

Reprint No. 75. "Highway Classification in Washington." R. G. Hennes. *Traffic Quart.*, Jan., 1953.

NORTHWEST CHROMITES SHOW PROMISING REFRACTORY PROPERTIES

(Continued from page 21)

Although the service performance of refractories cannot be determined positively by tests in the laboratory, the following general conclusions appear to be justified:

1. Chrome ore from the High Plateau and Oregon Chrome mines should be satisfactory substitutes for Rhodesian chrome ore for refractory uses.
2. Iron King and Chambers ores should be equal to Cuban ore in chrome refractories.
3. Tyson ore must be stabilized before it can be used successfully for refractories. Several successful techniques are given in the report.
4. Corrective additions (high-grade chrome ore) can be used to stabilize calcined Krome Corp. concentrate for use in refractories.
5. Laboratory brick prepared from Benbow, Mont., concentrate had physical properties superior to those of commercial chrome brick. Additions of high-grade ore or dead-burned magnesite will improve the product.

SCHOLEN: AIR EJECTOR FOR OZONATION

(Continued from page 30)

The water then cascaded over a series of splash boards to remove any residual ozone. The ejector was made of clear plastic with a tapering expander to be used with nozzles of different diameters of from 10 to 30 gpm and velocities of from 20 to 70 fps. Tapering the expander tends to keep the air chamber free of water when the ejector is discharging horizontally and allows an intimate gas-water contact on all sides. Tests run with the air supplied at the center of the jet gave more complete mixing than when air was supplied circumferentially. Tests showed clearly the superiority of the ejector over diffusion plates. Using less than one ppm ozone, the ejector sterilized badly polluted water, with a negligible detention period, thus showing the effectiveness of the ozone-water mixing. This ejector may also have uses for aeration or ozonation of certain industrial wastes, but because all parts are small, clogging may occur with such materials as domestic sewage. Aeration of a saturated water increased the dissolved oxygen content from 10.2 ppm to 13.0 ppm. The actual gain was probably greater since some degasification took place before the supersaturated sample could be analyzed. This research proved the efficiency of the ejector as a mixing device. Principles for design were formulated.

PASTELL: ELECTROLYTIC TITANIUM

(Continued from page 30)

2. With pure fused potassium fluotitanate as the electrolyte, a maximum conversion of 42.9 per cent was attained. Stainless steel electrodes were used in all of these runs and the molten charge was exposed to the atmosphere.

3. Pure fused potassium fluotitanate served as the electrolyte in a series of runs made in an inert atmosphere of hydrogen. Carbon and iron electrodes were employed. The maximum conversion obtained was 58.2 per cent.

4. Non-aqueous solutions of titanium tetrachloride in methyl alcohol, ethyl alcohol, acetonitrile, and ethyl ether were used as the electrolytes in an extensive series of runs in which the electrode materials were carbon, nickel, and copper. The maximum conversion obtained was 12.0 per cent.

Although not reaching the conversion percentages hoped for, the runs using molten potassium fluotitanate in a hydrogen atmosphere warrant further study under varying conditions with different electrode materials. A correlation between temperature, current density, and percentage conversion should be sought. Several titanates of the alkali and alkaline earth metals which are readily available might be used, with various molten salts for solvents.

PUBLICATIONS

of the

ENGINEERING EXPERIMENT STATION

UNIVERSITY OF WASHINGTON

Requests for copies of publications should be addressed to the Director, Engineering Experiment Station, University of Washington, Seattle 5.

BULLETINS

48. The Influence of Pipe Thickness on Re-Entrant Intake Losses. Charles William Harris. 35 pp. 1928.
56. Constant Flow Characteristic of the Plane Orifice in Proximity to Side Walls. Charles William Harris. 18 pp. 1931.
58. Preliminary Tests of Thirteen Washington Coals in a Powdered Coal Boiler Plant at the University of Washington. George Samuel Wilson, Harry Fagan Yancey, and Joseph Daniels. 27 pp. 1931.
60. An Electromagnetic Balance for Force Measurement of Current Control. Fred Scoville Eastman. 29 pp. 1932.
61. Hydraulic Flow Characteristics of a Square-Edged Intake. Charles William Harris. 21 pp. 1932.
67. The Doherty Washer Cooler. Sybren Ruurd Tymstra. 61 pp. 1932.
72. The Derivation of the Mean Temperature Difference Between a Saturated Gas and a Cooling Liquid, and also the Derivation of the Mean Velocity of Such Gas. Sybren Ruurd Tymstra. 19 pp. 1933.
74. The Deformation of Hard Grade Reinforcing Steel During and After Construction in a Reinforced Concrete Building. Sergius Ivan Sergev. 33 pp. 1933.
75. The Water Tube Gas Condenser. Sybren Ruurd Tymstra. 24 pp. 1934.
77. A Study of Fundamental Relations of the Mathematical Theory of Elasticity. Arthur Melvin Winslow. 25 pp. 1934.
78. Hydroelectric Power in Washington. Part III, A Brief on Proposed Grand Coulee Dams. Carl Edward Magnusson. 32 pp. 1935.
79. Cycloidal Propulsion in Air. Part I, Cycloidal Propulsion Theory; Part II, Cycloidal Propeller Development at the University of Washington. Frederick Kurt Kirsten. 87 pp. 1935.
81. Influence of Two Secondary Factors in Weir Measurement. Charles William Harris. 16 pp. 1935.
84. Equations for Calculating Three Phase Symmetrical Components. Gordon Russell Shuck. 32 pp. 1935.
85. Discharge of Three Commercial Cippoletti Weirs. Robert Bowman Van Horn. 32 pp. 1935.
87. Open Water Testing of Ship Models. Thomas McKie Rowlands. 20 pp. 1935.
88. The Properties of Quartz Sands Washed from Kaolins of the Pacific Northwest. Hewitt Wilson and Frank Joseph Zvanut. 42 pp. 1936.
90. Hydroelectric Power in Washington. Part IV, Regional Electric-Power Transmission. The Grid System. Carl Edward Magnusson. 51 pp. 1936.
91. The Analysis and Control of Landslides. Robert Graham Hennes. 57 pp. 1936.
92. Moment Equations. A Method of Analysis for Continuous Beams and Rigid Frames. Alfred Jensen. 88 pp. 1937.
93. Electric Power Markets in Washington. Part I, Electric Heating of Residences. Carl Edward Magnusson. 40 pp. 1937.
94. Evaporation and Surface Cooling. George Samuel Wilson and William Lyle Dudley. 18 pp. 1937.
95. Hydroelectric Power in Washington. Part V, A Bibliography of Technical Papers, 1926-1935. Carl Edward Magnusson. 204 pp. 1937.
96. Hydroelectric Power in Washington. Part VI, International Boundary Waters. Carl Edward Magnusson. 17 pp. 1937.
97. Strength of Concrete for Mixes of Various Proportions. Ira Leonard Collier. 28 pp. 1938.
98. Geology and Its Relation to the Occurrence of Oil in Washington. Charles Edwin Weaver. 16 pp. 1938.
99. Electric Power Markets in Washington. Part II, Residence Service Markets and a Regional Power Grid. Carl Edward Magnusson. 92 pp. 1938.
100. Modernization of a Transit System. Factors that Determine the Choice of a Vehicle. George Lisle Hoard. 36 pp. 1940.
101. Buckling Criteria and Design of Two-Story Columns. Sergius I. Sergev. 48 pp. 1940.
102. An Investigation of Prestressed Stays. T. M. Rowlands and F. C. Smith. 36 pp. 1941.
103. Bismuth Bridge Magnetic Flux Meter. George Sherman Smith. 48 pp. 1940.
104. The Telechronometer, Telephone Service Measurement in Units of Time. Lyall Baker Cochran. 68 pp. 1941.
105. Theory of Flexure of Structural Members of Non-uniform Section. Alfred L. Miller. 68 pp. 1940.
106. The Shearing Strength of Cement Mortar. Frederick C. Smith and Robert Q. Brown. 32 pp. 1941.
107. A Geologic Interpretation of the Failure of the Cedar Reservoir, Washington. J. Hoover Mackin. 30 pp. 1941.
108. Silica Sands of Washington. Hewitt Wilson, Kenneth G. Skinner and Albert H. Couch. 76 pp. 1942.
109. The Number of Teeth in Contact as a Vibration Factor in Involute Cut Gears. Sybren Ruurd Tymstra. 16 pp. 1942.
110. Solutions for Torsional Vibration Frequencies by Energy Method. Arthur Melvin Winslow. 22 pp. 1943.
111. Stabilized Earth Blocks for Protective Construction. Robert G. Hennes. 24 pp. 1943.
112. Hydraulic Models. Charles W. Harris. 17 pp. 1944.
114. The Effect of Shearing Forces on the Deflection and Strength of Beams. Sergius I. Sergev. 20 pp. 1947.
115. The Influence of Random Roughness on Flow in Pipes. Charles W. Harris. 19 pp. 1949.
116. Aerodynamic Stability of Suspension Bridges with Special Reference to the Tacoma Narrows Bridge. Part I, Investigations Prior to October, 1941. F. B. Farquharson. 103 pp. 1949.
116. Aerodynamic Stability of Suspension Bridges with Special Reference to the Tacoma Narrows Bridge. Part II, Mathematical Analyses. F. C. Smith and G. S. Vincent. 63 pp. 1950.
116. Aerodynamic Stability of Suspension Bridges with Special Reference to the Tacoma Narrows Bridge. Part III, The Investigation of Models of the Original Tacoma Narrows Bridge Under the Action of Wind. F. B. Farquharson. 125 pp. 1952.
116. Aerodynamic Stability of Suspension Bridges with Special Reference to the Tacoma Narrows Bridge. Part IV, The Investigation of Models of the New Tacoma Narrows Bridge Under the Action of Wind. F. B. Farquharson. (In preparation.)
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